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FIBER OPTICS REMOTING OF TERMINAL RADAR AND BEACON SIGNALS.(U)
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Fiber Optics Remoting of Terminal Radar and Beacon Signals

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May 1982

Final Report

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16. Abstract

This report discusses the study phase of the terminal radar-beacon fiber optics remoting project. Fiber optics technology is discussed and applied to the remoting of airport surveillance radar (ASR) and air traffic control beacon interrogator (ATCBI) video and control signals. The requirements of this system are outlined and an engineering model, using multiplexed and nonmultiplexed video transmissions, is specified for installation at the Federal Aviation Administration (FAA) Technical Center. Tests to be conducted on this system are briefly outlined. Cost estimates are presented as well as suggested sources of supply for the fiber optic components. The interface to the ASR and ATCBI systems is described. It is recommended that the system be built by the Technical Center. A schedule for completion of the remainder of the project is presented.

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METRIC CONVERSION FACTORS

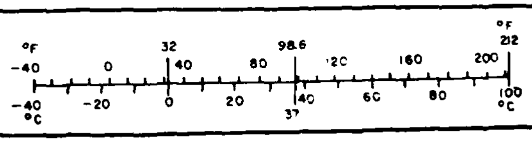
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 exactly. For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

PURPOSE.

In response to request AAF-530-80-3 (via Form 9550-1), Fiber Optics Remoting, the first phase of a proposed two-phase effort has been initiated at the Federal Aviation Administration (FAA) Technical Center to investigate techniques for remoting terminal radar and beacon information to the remote indicator site using fiber optics. This report covers the system's analysis and definition study, in particular:

1. A study of fiber optics communications technology.

2. The specification of a fiber optics remoting system test bed to be installed at the Technical Center in phase II. The start of phase II is awaiting Airway Facilities approval.

3. The development of a general test plan for the proposed fiber optics system. Phase II of this effort, if pursued, will consist of the hardware design, procurement, test, and evaluation of a fiber optics remoting system interfaced with a terminal radar-beacon system at the FAA Technical Center.

BACKGROUND.

The FAA currently uses coaxial and multiconductor cables to remote airport surveillance radar (ASR) and air traffic control beacon interrogator (ATCBI) signals between the radar site and the indicator site. A major problem with these cables is damage due to lightning induced surges. Other problems that occur are deterioration due to water penetration, aging, and 60-hertz (Hz) hum due to nearby power conductors. Fiber optic remoting of these signals could result in improved performance and maintenance cost reduction by reducing or eliminating each of these primary problem areas. A list of advantages and disadvantages of a fiber optics remoting system are as follows:

1. Advantages.

   a. Extremely resistant to electromagnetic interference including lightning and interference from power or signal cables.

   b. No ground loop problems and complete electrical isolation of signal transmission paths.

   c. No short circuits.

   d. No crosstalk between optical cables.

   e. No electrical code requirements.

   f. Higher bandwidth digital or analog transmission than coaxial cable systems.

   g. Smaller and lighter than coaxial cable or multiconductor systems.

h. Fewer oxidation or corrosion problems than coaxial cable or multiconductor systems.

2. Disadvantages.

a. Often higher cost of installation than for a coaxial cable or multiconductor system.

b. May require more electronics.

c. Working with glass fiber cable requires special training in making repairs, splices, etc.

FIBER OPTICS SYSTEMS ANALYSIS AND DESIGN CONSIDERATIONS

SIGNAL REQUIREMENTS.

The signals that are required to be remoted for a typical terminal radar site are listed in table 1 along with their required transmission parameters. These parameters were determined by the required signal fidelity and were estimated in the following ways.

The requirements for remoting of ASR radar video vary depending upon the use of the video signal. A radar plan position indicator (PPI) display has, at most, a 15 decibel (dB) dynamic range, while most digital processing hardware requires the full system dynamic range of the radar, about 30 to 40 dB. Beacon signals require only about 15 dB dynamic range since the signals are predetected and shaped at the receiver. It seems safe to assume that 40 dB will meet all FAA radar remoting requirements now and in the future. The video signal of an ASR has a bandwidth of about 1 megahertz (MHz). The fast rise-time pulses of a beacon signal require somewhat more bandwidth than this. In both cases a video bandwidth of 5 MHz should prove adequate.

The radar trigger provides the zero-range reference for the radar video. In all ASR radars, this signal occurs between 50 and 100 microseconds (μs) before the actual radar video. The trigger occurs at the radar or beacon pulse repetition frequency (PRF) (about 1000 and 300 Hz, respectively) and has a duration of about 1 μs. If a trigger is absent, the display will not sweep or the automatic processor will not search for data so the consequences are not severe. However, if additional triggers are provided or if the trigger occurs at the wrong time, erroneous information will be presented. This is not acceptable, so the missed detection and false alarm probabilities are set at 10^{-4} and 10^{-6}, respectively. This provides for less than one missed trigger in 10 seconds and one false trigger in 1,000 seconds. While this level of error could be tolerated, much higher levels of performance are expected of the system. The jitter of the trigger relative to actual zero video time should be a small fraction of a range gate (typically, one pulse width or 0.600 to 0.833 μs). Sixty nanoseconds (ns) is less than one-tenth of a range gate in all cases. The relative delay of the video and trigger channels must be identical (again, using the same reasoning, to within about 60 ns) to avoid misregistration or processing errors.

TABLE 1. SIGNALS REQUIRED FOR OPERATION OF A TERMINAL RADAR-BEACON SITE

Signal Name	Quantity	Dynamic Range (dB)	Bandwidth or Pulse Width	Probability of Missed Detection	Probability of False Alarm	Pulse Jitter	Differential Delay
Radar Video	2	30-40	1 MHz				
Beacon Video	1	15	5 MHz				
Radar Trigger	2		1 μs	10^{-4}	10^{-6}	60 ns	60 ns
Beacon Trigger	1		1 μs	10^{-4}	10^{-6}	60 ns	60 ns
Azimuth Change Pulse	2		22 μs	10^{-4}	10^{-4}		500 μs
Azimuth Reference Pulse	2		22 μs	10^{-4}	10^{-8}		500 μs
Intercom	2		3 kHz				
Control and Readback	100		d.c.	10^{-3}	10^{-3}		1 sec

In addition to radar and beacon video and trigger signals, a great many other signals are necessary for the operation of a radar-beacon system. The system requires azimuth change pulses (ACP's) and azimuth reference pulses (ARP's) to indicate the direction of the antenna beam. In addition, there are many control and readback lines to allow the operator to change radar or beacon parameters and to receive positive verification of a change, and an intercom system to facilitate communications between the radar technician and radar operator.

Each time the radar antenna crosses north, the ARP is generated and used to synchronize the display. The duration of the ARP is 22 μs.

As the antenna continues to rotate, ACP's are generated each time the antenna rotates a small fixed amount. Each time the antenna completes one full rotation, 4,096 of these pulses occur. These ACP's are also 22 μs in duration and occur at a rate of about 1000 Hz (1 kilohertz (kHz)) when the antenna is rotating at 12.5 revolutions per minute (rpm).

If an ACP is missed or if an additional ACP is detected, the error will be insignificant so a probability of detection or false alarm rate of 10^{-4} is acceptable. This corresponds to one error every 10 scans. If an ARP is missed, the display will coast through north without error; however, if an additional ARP is included, the display will be reset to north no matter what direction the antenna is pointing. This is clearly intolerable. A probability of false alarm on this channel of 10^{-8} would result in this occurring about once a day. By using windowing techniques this could be reduced to one occurance in several months of operation.

The control and readback signals consist of separate lines which are grounded to activate and opened to inhibit. There are about 100 channels, depending on the exact site configuration.

Each ASR site has an intercom system. This requires two bidirectional audio channels with a bandwidth of about 3 kHz. The signaling and other intercom functions can be handled in the same way as the control and readback signals.

BASEBAND FIBER OPTIC LINK PERFORMANCE.

Several options will be considered for remoting the signals discussed in the previous section. At the present time, trigger and video signals are remoted via coaxial cable, and the other signals are remoted via multiconductor cable and shielded twisted pair cables. This system will be refered to as the coaxial system. The fiber optics systems to be discussed typically use a fiber optic link which transmits a signal modulated in some manner by the radar video or other message. In all of the examples and analyses to follow, a 5-MHz bandwidth radar video signal requiring a 40 dB dynamic range will be assumed because this is the most stringent remoting requirement of all signals to be remoted. The simplest method is to use no intermediate modulation at all, that is, to vary the intensity of the light directly by the radar signal. This method is called baseband. Baseband signal transmission can be improved upon by using modulation. An increase in transmitted bandwidth can result in an improved signal-to-noise ratio after demodulation or equivalently in a lower transmitted power requirement. The baseband performance of the fiber optic link provides a basis for computing the performance of other modulation techniques and, therefore, will be discussed first.

A block diagram for a typical baseband fiber optic link is shown in figure 1. Such a link consists of an intensity modulated source coupled to an optical fiber which, in turn, is connected to an optical detector and amplifier. The combination of the source and driver is called an optical transmitter. The combination of optical detector and amplifier is called an optical receiver. Each of these components will be discussed briefly. (A more detailed discussion of these topics is contained in appendix A.) Each device discussed will be illustrated by an example chosen from currently available components. These components will be used to estimate the performance of a typical fiber optic link system. The components for this analysis were selected only because they are typical and allow rather simple calculations of the performance of these systems. It is not meant to indicate the state of the art, but only to provide reasonable values of system performance. No endorsement of these products is intended.

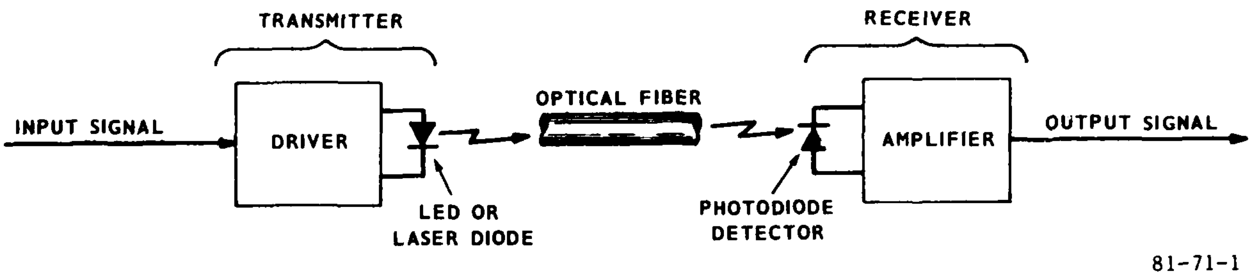

FIGURE 1. TYPICAL BASEBAND FIBER OPTIC LINK

OPTICAL TRANSMITTER CHARACTERISTICS. Optical communications light sources are dominated by semiconductor laser diodes and light emitting diodes (LED). These devices differ from each other in several important aspects. The laser diode typically has a greater power output than the LED. The laser diode generates a more collimated beam, proportionately, and more of its power can be coupled into the optical fiber. For the components selected for analysis, table 2 shows this difference to be 15 dB. Laser diodes are inherently faster than LED's. This can be seen from table 2 by observing that the rise time of the laser diode is less than 1 ns, while the risetime of the LED is 3 ns. Laser diodes are also more expensive than LED's. LED's are linear devices well suited to analog modulation, while Laser diodes are inherently nonlinear devices more suited to on-off digital signaling but still usable for analog applications where some nonlinearity can be tolerated.

Laser diodes are more temperature dependent than LED's and require more complex and expensive compensation circuitry. Therefore, LED's are to be preferred if the higher performance of laser diodes is not required.

TABLE 2. OPTICAL SOURCE SPECIFICATIONS

	LED RCA C86009E	Laser Diode RCA C86010E
Emission Wavelength	820 nm	820 nm
Pigtail Core Diameter (Siecor 112 Optical Cable)	62.5 μm	62.5 μm
Power Output	0.06 mW	2 mW
Current Required	200 mA	300-400 mA
Forward Voltage Drop	2 V	2 V
Rise Time	3 ns	1 ns
Peak Current (0.1 s duration)	1 A	
Peak Power Output		250 mW

Note:

nm = nanometer
μm = micrometer
mW = milliwatts
mA = milliamperes
V = volts
A = ampere

OPTICAL FIBER CHARACTERISTICS. Optical fiber is used to transmit light from the source to the detector. Light is contained within the fiber either by total internal reflection or by refraction. The index of refraction of the center of the fiber, called the core, is always greater than the index of refraction of the outer part of the fiber, called the cladding. If this change in refractive index occurs suddenly, the fiber is called a step index fiber. If the refractive index changes gradually, the fiber is called a graded index fiber. Graded index fibers typically have a higher bandwidth than step index fibers and, usually, a lower attenuation. Typical specifications for a graded index fiber cable are shown in table 3. The attenuation of some optical fibers is a sensitive function of light frequency so the cable specifications should be determined at the frequency of the source. The source frequency and cable measurement frequency differ slightly in this analysis, but since the differences are small and this is not a design analysis, errors introduced will be ignored.

Connectors are typically used to join the source and detector to the optical fiber. The mechanical fiber alignment, which is possible with present techniques, allows connectors to be made with average attenuations below 2 dB. On the other hand, splices need be made only once and are carefully aligned, sometimes by observing the ends with a microscope, and then glued in place. Splice attenuations below 0.2 dB are typical.

TABLE 3. OPTICAL CABLE SPECIFICATIONS

	Siecor, FT3C686P, Buried Cable, 6 Graded Index Fibers
Attenuation	4.5 dB/km at 850 nm
Bandwidth	500 MHz/km
Numerical Aperture	0.2
Core Diameter	50 μm
Fiber Diameter	125 μm
Fiber Coating Diameter	250 μm

OPTICAL RECEIVER CHARACTERISTICS. An optical receiver consists of a photo-detector followed by an amplifier. The two types of photo-detectors used most often in optical communications are the positive-intrinsic-negative (PIN) photodiode and the avalanche photodiode (APD). The difference between the two is that the APD is designed to be operated at the higher voltages necessary for avalanche gain. This avalanche gain increases sensitivity about 30 to 100 times. Table 4 shows typical characteristics of PIN and APD detectors. The noise equivalent power is a measure of the optical noise power required at the input of a noiseless receiver necessary to produce the same electrical noise power at its output as is produced by thermal noise in the real, noisy receiver. This value is a good measure of the optical receivers sensitivity and by comparing these values in table 4 the APD is seen to be about 100 times more sensitive. The signal-to-noise ratio (SNR) for a photodiode is shown in appendix A equation A-13 to be:

$$SNR = \frac{2[(P\eta/h\upsilon)eM]^2}{(3P\eta/h\upsilon)e^2M^{2.1}B + 2eI_dBM + 4\ KTB/R} \tag{1}$$

where:

SNR is the signal-to-noise ratio,

P is the optical signal power,

M is the avalanche gain (M = 1 for PIN diodes),

B is the bandwidth of receiver,

I_d is the dark current, usually small enough to neglect,

4 KTB/R is the mean squared thermal noise current, and the quantity $(3\ P\eta/h\nu)e^2M^{2.1}B$ is the mean squared shot noise current due to the light incident on the photodiode.

Typically when M is small, as it is for the PIN diode, the thermal noise component dominates.

TABLE 4. OPTICAL DETECTOR SPECIFICATION

	PIN Detector RCA C30847E	APD Detector RCA C30917E
Detection Wavelength	400-1100 nm	400-1100 nm
Maximum Flux Input	5 mW	0.0013 mW
Fiber Numerical Aperture		0.6
Fiber Refractive Index		1.61
Bias Voltage Required	45 V	180-250 V
Forward Transfer Ratio	3.2×10^{3} V/W	3.4×10^{5} V/W
Noise Equivalent Power	4.7×10^{-12} W/$\sqrt{\text{Hz}}$	4.4×10^{-14} W/$\sqrt{\text{Hz}}$
Output Noise Voltage Density	1.5×10^{-8} V/$\sqrt{\text{Hz}}$	1.5×10^{-8} V/$\sqrt{\text{Hz}}$
Amplifier Output Impedence	25 ohms	25 ohms
Frequency Response (-3 dB)	0-50 MHz	0-50 MHz
Linear Range	80 dB	70 dB
Risetime	9 ns	9 ns

As the avalanche gain increases, so does the sensitivity until the shot noise term becomes important. After this point, the sensitivity will again decrease. It is important, then, to consider the effect of shot noise in optical receivers using the APD. The SNR for a shot noise limited photodiode is given in appendix A, equation A-15 as:

$$\text{SNR(APD)} = (2P\eta/h\nu)/3BM^{0.1} = \frac{0.42}{h\nu}\ \frac{P\eta}{B} \tag{2}$$

If the minimum detectable optical power is defined as the power necessary to make the SNR equal unity, then this power is given by:

$$P(\min) = h\nu B/0.42\eta \tag{3}$$

Using an emission frequency of $\nu = 3.6 \times 10^{14}$ and a quantum efficiency of $\eta = 0.8$ results in:

$$P(\min) = (7.21 \times 10^{-16})B \ \text{mW} \tag{4}$$

Plotting this versus the noise equivalent power (figure 2) shows that P(min) is much less then the noise equivalent power for all bandwidths of interest; hence, in this analysis shot noise effects can be neglected.

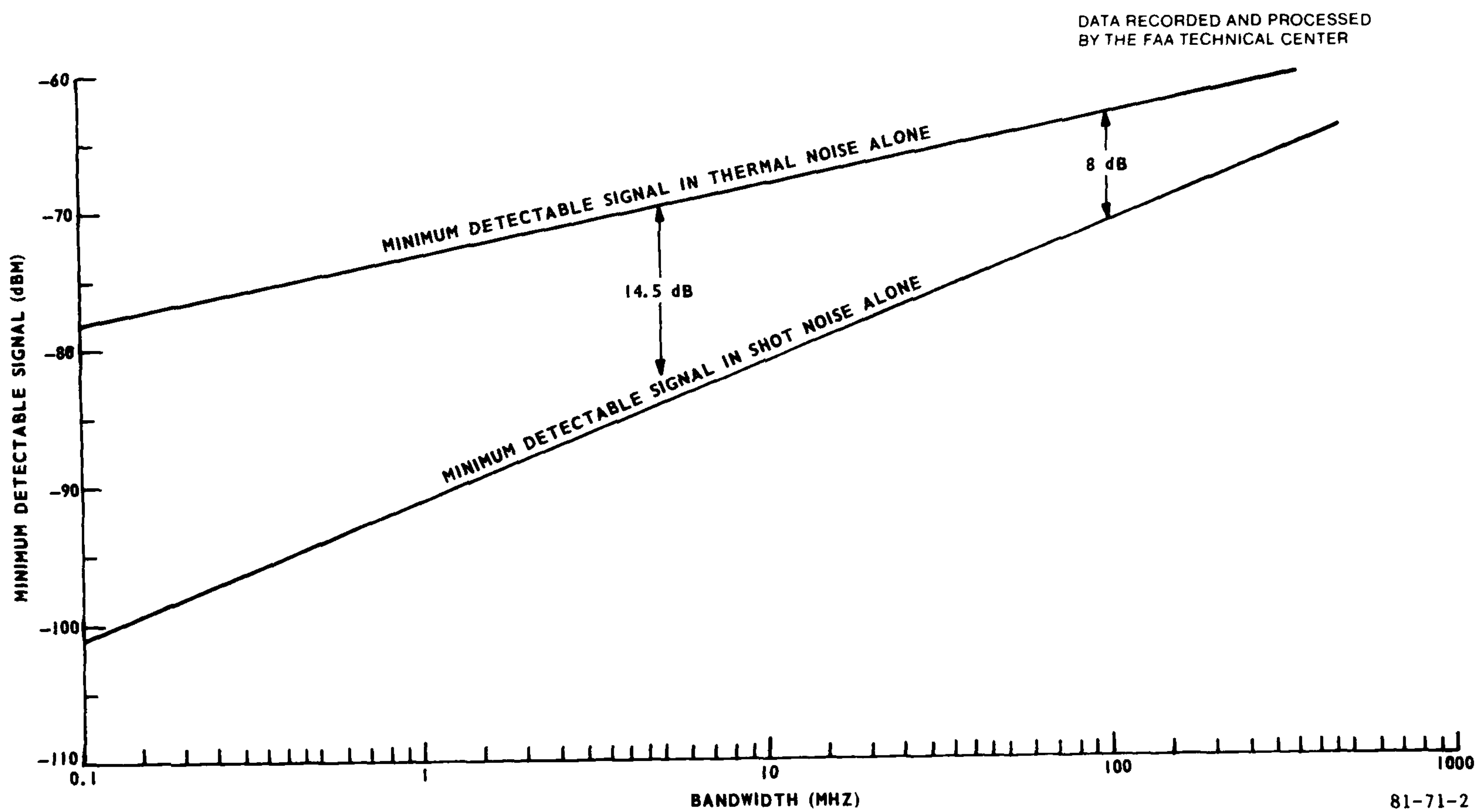

FIGURE 2. NOISE EQUIVALENT POWER OF THERMAL AND SHOT NOISE VERSUS BANDWIDTH FOR C30917E AVALANCHE PHOTO DETECTOR

The APD is both more expensive and more temperature dependent than the PIN diode. The temperature dependence requires compensating circuitry similar to that used for the laser diode. These additional costs are often justified to obtain the benefit of another 20 dB of SNR. The SNR performance of these links will be examined in the following paragraphs.

The ultimate measure of a communications system is its channel capacity. Channel capacity is a measure of maximum information transmission possible per unit time and its units are bits per second. In this sense, the term bits is used as a measure of information and applies equally well to analog and digitial transmission, although it is more difficult to compute for an analog system.

The channel capacity is related to the channel bandwidth and SRN by the Hartley-Shannon law,

$$C = B \operatorname{Log}(1 + SNR) \tag{5}$$

where:

C is the channel capacity in bits per second,

B is the bandwidth in Hz, and

SNR is the channel signal-to-noise ratio.

It should be emphasized that the Hartley-Shannon law provides a theoretical limit to information transfer and, furthermore, points out its relationship to bandwidth and SNR. Though it does not tell us how to build a system which can operate at this capacity, it does provide an upper bound estimate on the performance to be expected from a real system. The remainder of this section will be concerned with calculating maximum signal-to-noise ratio (dynamic range) and channel bandwidth.

DYNAMIC RANGE. The channel dynamic range will be computed for the devices chosen in the previous section. The calculation will be performed first for the PIN diode, LED combination, and the changes resulting from use of a laser diode, APD, or both will be calculated. The attenuation and power budget for this system is shown in table 5.

A 4-kilometer (km) transmission distance is assumed giving a total cable attenuation of 18 dB. It is assumed that the link is installed with three splices of 1 dB attenuation each. The source coupling and detector coupling attenuation are each estimated to be 2 dB because connectors are used in each case. Thus, the total transmission loss is 25 dB. The average source power is added to the transmission loss to determine the average detector power input. The dynamic range is then computed by taking the ratio of the maximum signal available to the minimum signal detectable, defined by letting the signal-to-noise ratio be unity.

Since shot noise has been shown to be insignificant, the minimum detectable signal power will be equal to the detector noise equivalent power.

The optical dynamic range is shown in table 5 to be 16 dB for a channel bandwidth of 1 MHz. Since optical power will be linearly converted into electrical current by the detector, the dynamic range of the complete link will be twice the dynamic range of the optical portion. Hence, the system dynamic range will be 32 dB for a 1 MHz bandwidth. For an arbitrary bandwidth the dynamic range will be

$$SNR(max) = 32 \text{ dB} - 10 \log(B) \text{dB} \qquad (6)$$

where:

SNR (MAX) is the system dynamic range and B is the channel bandwidth.

The attenuation margin is a measure of the additional optical power available at the source above that required to just meet requirements. A radar video channel requires about 40 dB dynamic range with a bandwidth of 5 MHz. For the typical systems discussed, the attenuation margin is listed in table 6. In addition to the attenuation margin, the length of 4.5 dB/km fiber optic cable which can be used in each system is also indicated.

TABLE 5. LED — PIN DIODE, 4 km, ATTENUATION AND POWER BUDGET

Cable Attenuation (4 km x 4.5 dB/km)	18 dB
Cable Splices (3 splices x 1 dB/splice)	3 dB
Source Coupling Loss	2 dB
Detector Coupling Loss	2 dB
Total Transmission Attenuation	25 dB
Maximum LED Power Output (0.06 mW)	-12 dBm
Maximum Detector Input Average Power	-37 dBm
Noise Equivalent Power (4.7 x 10 $W/\sqrt{Hz}$) x (1 MHz Bandwidth)$^{1/2}$	-53 dBm
Optical Dynamic Range (1 MHz)	16 dB
Electrical Dynamic Range (1 MHz)	32 dB

TABLE 6. ATTENUATION MARGIN FOR FOUR BASEBAND FIBER OPTIC LINKS OF 40 dB DYNAMIC RANGE AND 5 MHz BANDWIDTH

Attenuation Margin of a 4 km Link		Usable Length of 4.5 dB/km Cable
LED-PIN	-4 dB	3.1 km
Laser-PIN	11 dB	6.5 km
LED-APD	16 dB	7.5 km
Laser-APD	31 dB	11.0 km

MODULATED FIBER OPTIC LINK PERFORMANCE.

The block diagram of a typical modulated fiber optic link is shown in figure 3. The modulator transforms the input signal into a form more suitable for transmission on the optical link. Modulation is used to transmit more than one signal on the channel (multiplexing) and to improve the overall message SNR (wideband noise reduction).

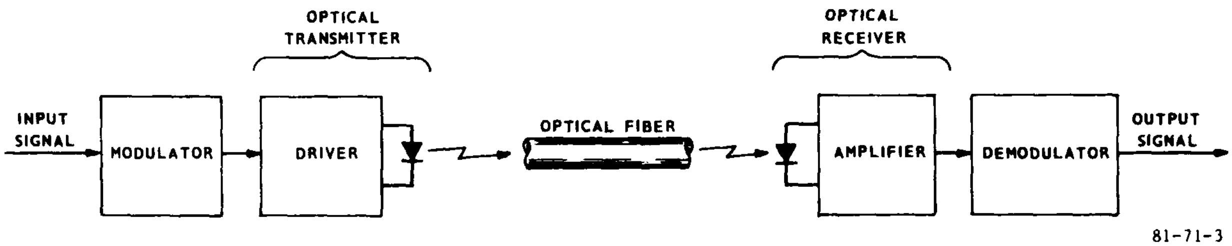

FIGURE 3. BLOCK DIAGRAM OF MODULATED FIBER OPTIC LINK

Fiber optic links are inherently unipolar since information is conveyed via the intensity of light which can not be negative. Many kinds of modulation required a bipolar channel and, when this is the case, a d.c. bias must be added to the source drive signal to prevent the source from completely turning off. This d.c. bias power would normally be used for the message and so reduces the effective transmission SNR by 3 dB or more. Typically, a fiber optic system's dynamic range is limited by the maximum average or peak source power. When a multiplexed system is used, the power is usually equally divided among all carriers and the effective SNR per channel is reduced proportionally. The bandwidth of a multiplexed system is found by adding the bandwidths of each modulated signal and allowing for no-signal areas, called guard bands, to separate adjacent signals. In the following analysis, these guard bands have been ignored for simplicity.

Some kinds of modulation exhibit the property of wideband noise reduction. In a system with this property, increased transmitted bandwidth can be used to gain an improvement in SNR after demodulation. In the following sections, several modulation techniques will be discussed to examine their bandwidth, noise reduction, and other properties. To properly compare various modulation schemes, the required characteristics of the fiber optic channel necessary to transmit a standard signal of 5 MHz bandwidth and 40 dB required dynamic range will be estimated for each modulation.

This comparison is presented in figure 4. The ordinate of the graph shows the required channel dynamic range at the baseband bandwidth and is independent of the required bandwidth. The abscissa of the graph shows the required bandwidth to transmit the modulated signal.

BASEBAND. The baseband system uses no modulation so the transmission requirements are the same as the message requirements; i.e., 40 dB of dynamic range and a bandwidth of 5 MHz. This performance is indicated on figure 5 as a point at 40 dB and 5 MHz. The fact that the link is unipolar is of no consequence because the radar signal is also unipolar.

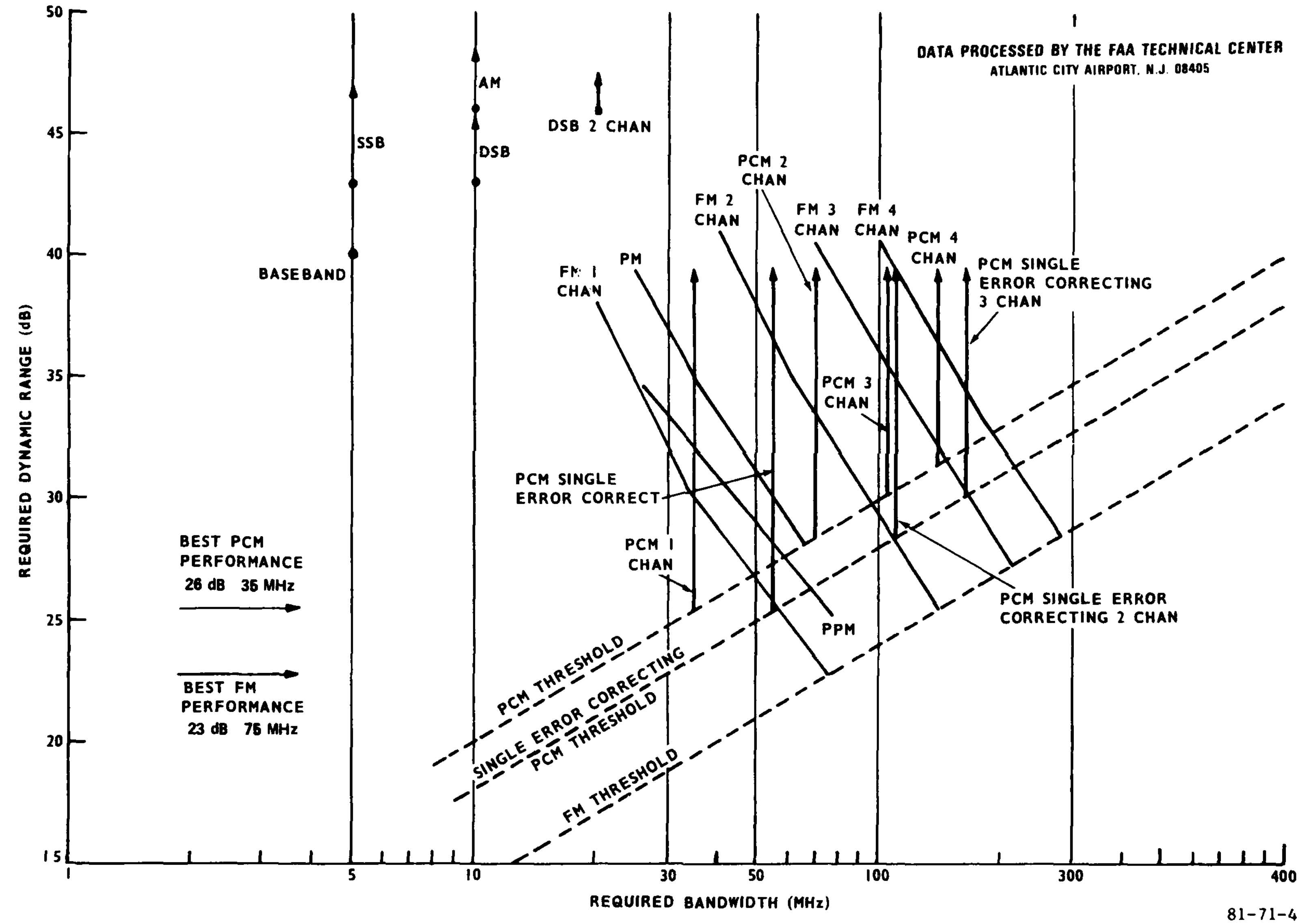

FIGURE 4. CHANNEL REQUIREMENTS FOR TRANSMISSION OF A 5 MHz, 40 dB SIGNAL USING VARIOUS MODULATIONS

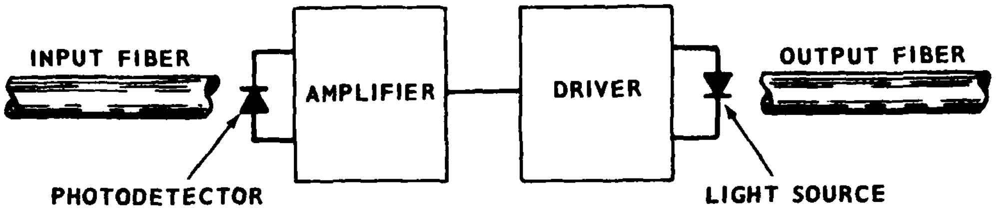

FIGURE 5. BLOCK DIAGRAM OF ANALOG REPEATER

DOUBLE SIDEBAND. A double sideband (DSB) signal is generated by multiplying the message signal by a sinusoidal wave form of a higher frequency called the carrier. The effect of DSB is to translate the message spectrum to the carrier frequency. Each sideband of the transmitted DSB signal has a bandwidth equal to the baseband message bandwidth, W, so the transmission bandwidth of the DSB signal is twice the message bandwidth or 2W. The SNR is reduced by DSB operation, but DSB can be used for multiplexing. Its chief advantage is simplicity.

SINGLE SIDEBAND. Single sideband (SSB) modulation can be thought of as DSB with one of the sidebands removed. SSB has a transmission bandwidth equal to the message bandwidth and, yet, provides no SNR improvement over DSB. SSB is more difficult to implemert than DSB and is used only when bandwidth conservation is especially important. This rarely occurs in the case in a fiber optic system.

AMPLITUDE MODULATION. Amplitude modulation (AM) is basically DSB with the exception that a bias voltage is added to the message signal to prevent the carrier from reversing phase when the message is negative. Since power is required to transmit this bias signal, its SNR is inferior to that of DSB, SSB, and baseband. It is used when the receiver must be made as simple as possible, but it is not often used in fiber optic systems.

FREQUENCY MODULATION. A frequency modulation (FM) system varies the carrier frequency in proportion to the input signal level. It is characterized by the peak frequency deviation from the carrier frequency which is most often expressed as the frequency deviation ratio

$$D = f_d/W \tag{7}$$

Here D is the frequency deviation ratio, f_d is the peak frequency deviation, and W is the message bandwidth.

FM is a nonlinear process and, therefore, complications naturally occur when trying to compute the spectrum of the modulated signal. To avoid these difficulties, an emperical expression (Carson's Rule) is often used. Carson's Rule relates the transmission bandwidth (B) to the message bandwidth (W) and frequency deviation ratio as follows (reference 1):

$$B = 2\ (D + 1)\ W \tag{8}$$

The signal to noise ratio is given in reference 2:

$$SNR_D = 3D^2\overline{x^2}z \tag{9}$$

where:

SNR is the detected SNR,

D is the frequency deviation ratio,

$\overline{x^2}$ is the normalized signal average power, and

z is the baseband SNR.

Combining equations 8 and 9, correcting for the 3 dB reduction due to d.c. bias, and letting $\overline{x^2} = 1$, its maximum value, results in

$$z = \frac{2}{3}\left[\frac{B}{2W} - 1\right]^{-2} SNR_{(max)} \tag{10}$$

where again SNR (max) is the system dynamic range.

Figure 4 shows this function for W equal to 5 MHz and SNR (max) equal to 40 dB. Increasing the transmitted bandwidth increases the noise with which the modulated signal must compete.

As this occurs, impulses gradually start to occur at the demodulator output. For proper operation, the probability of an impulse occuring should be less than the radars false alarm probability so the maximum impulse rate, in this case, must be about 10^{-6} sec^{-1}. The impulse rate is given in reference 3 as:

$$R \approx \frac{fd}{\pi\sqrt{12}} \operatorname{erfc}\left[(SNR)^{\frac{1}{2}}\right] \tag{11}$$

where:

R is the average impulse rate,
fd is the frequency deviation, and
SNR is the channel signal-to-noise ratio.

Solving this equation for $R = 10^{-6}$ sec^{-1} yields a value of SNR of about 11 dB for all practical cases. This line is plotted dashed at the lower right of figure 4. Only FM modulation with parameters above the line are usable.

PHASE MODULATION. Phase modulation (PM) is created by varying the instantaneous phase of a carrier in proportion to the message signal. The performance characteristics of PM are very similiar to FM. The pertinant equations are given in references 4 and 5 as:

$$B = 2\left(\frac{\Delta\Phi}{2} + 1\right) W \tag{12}$$

$$SNR = \frac{1}{2} (\Delta\phi)^2 \overline{x^2} z \qquad (13)$$

$$z = 2 \left[\frac{B}{2W} - 1\right]^{-2} SNR_{(max)} \qquad (14)$$

where all symbols are the same as in the FM case and $\Delta\phi$ is the peak phase deviation. Threshold effects also occur in PM. However, a more important limitation in this application is that $\Delta\phi \leq \pi$ to avoid ambiguity. The performance of PM in figure 4 is seen to be about 5 dB poorer than that for FM.

PULSE POSITION MODULATION. Using pulse position modulation, the position (phase) of a narrow pulse varies in proportion to the message signal. The signal-to-noise ratio of the demodulated signal depends on the pulse rise time which, in turn, depends on the transmission bandwidth. By choosing the parameters of the PPM signal to exactly match this bandwidth, the optimum signal-to-noise ratio is found in reference 6 to be approximately

$$z = 8 \left(\frac{B}{W}\right)^{-2} SNR_{(max)} \qquad (15)$$

where:

- z is the baseband signal-to-noise ratio required,
- B is the transmission bandwidth,
- W is the message bandwidth, and
- SNR is the signal-to-noise ratio of the demodulated signal.

From the graph of figure 4, this performance is seen to fall between phase modulation and frequency modulation. Another type of pulse modulation, pulse duration modulation (PDM), also exhibits wideband noise reduction but is not considered here since it is inferior to PPM.

PULSE CODE MODULATION. To produce pulse code modulation (PCM), the message signal is sampled, quantized, and transmitted digitally on the channel. Demodulation consists of converting the digital signal back to voltage levels and filtering the resultant signal to remove switching noise. The SNR is determined by the amount of quantization provided by the modulator and is nearly independent of the channel quality. A good estimate of the SNR due to quantization is 6 dB per each bit generated (reference 7); therefore, to achieve 40 dB at least seven bits must be used. The transmission requirements are determined by the bandwidth and error rate requirements of the digital bit stream. The transmission bandwidth requirement is about equal to the product of the message bandwidth and the number of bits or, for a single channel, 35 MHz.

The error rate of the digital signal is determined by the probability of false alarm acceptable in the radar channel. This probability is about 10^{-6} per sample, or four false alarms per scan, and is easily tolerated by the radar system. If it is assumed that an error in any bit of a sample will cause a false alarm, the probability of false alarm will be seven times the channel's error rate. To achieve a probability of false alarm of 10^{-6} then, will require a probability of error of 1.43×10^{-7}. To provide this performance, a channel SNR of 17 dB is required. Figure 4 shows PCM to be superior to FM at the transmission bandwidth required for PCM, but FM to be superior near the FM threshold. One is led to wonder if the introduction of an error correcting code, which would increase the bandwidth and decrease the threshold of PCM, would provide an improvement in required SNR. Unfortunately, in this case, the improvement due to error correction is almost exactly cancelled by the rise in noise level brought about by the increased transmission the bandwidth required. Both single and double error correcting codes show this same result.

REPEATERS.

A repeater is used to allow long distance transmission on a fiber optic link. Fiber optic repeaters consist, basically, of an optical receiver and transmitter back to back. The simplest repeaters supply only amplification while more complex regenerative repeaters provide a margin of noise supression.

The block diagram of a typical analog fiber optic repeater is shown in figure 5. The optical signal is simply detected, amplified, and retransmitted. The detector necessarily introduces noise which is unavoidably amplified along with the signal. If all of the repeaters are designed to amplify the signal just enough to make up for the channel's loss, the noise contribution of each repeater to the final output will be the same and additive, so the SNR of the overall channel will be given as (reference 8):

$$SNR_M = \left(\frac{1}{M}\right) SNR_1 \tag{16}$$

where:

SNR_M is the signal-to-noise ratio of M cascaded fiber optic links, and
SNR_1 is the SNR of an individual link.

The block diagram of a regenerative repeater is shown in figure 6. This kind of repeater provides a significant improvement in SNR for digital signals when compared to the anolog repeater previously discussed.

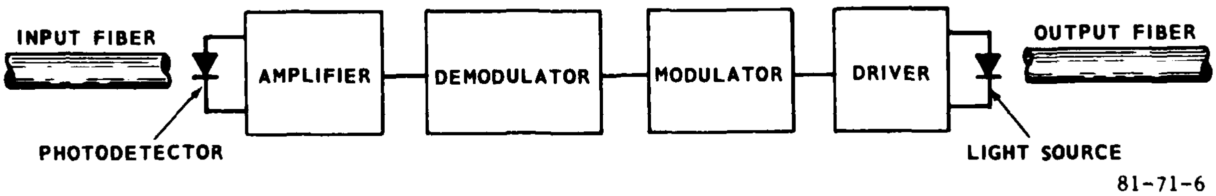

FIGURE 6. BLOCK DIAGRAM OF A REGENERATIVE REPEATER

The process of demodulation introduces a small number of independant errors each time it is performed. For a number, M, of repeaters the probability of error will increase M times. The error probability decreases quite rapidly when SNR is increased, so an increase in error rate of M times can be offset by a modest SNR increase instead of an increase in SNR of M times, as would be the case with an analog repeater. PCM is, therefore, clearly superior when a large number of repeaters need be used.

Reliability is one of the major concerns in repeater installations. One reason fiber optics signal remoting shows so much promise in this application is its resistance to lighting induced failure. When repeaters are used, however, conducters used for power can couple surges into the repeaters causing them to fail. Therefore, if not properly designed the system may be no better than the original coaxial system. In a completely multiplexed system such a loss would cause a complete outage, hence, some degree of redundancy would be required. To reduce this problem, repeaters should be protected from surges.

MULTIPLEXING.

Multiplexing is a technique to transmit several signals on one communications channel. The two techniques usually employed are time division multiplexing (TDM) and frequency division multiplexing (FDM). TDM is used on digital channels while FDM is most often used on analog channels. As a general rule, a multiplexed system requires at least as great a bandwidth as the sum of the bandwidths of the transmitted signals. This and the signal-to-noise ratio requirements were discussed in a previous section. It is the purpose of this section to discuss some of the other trade-offs which are applied to multiplex system design.

In general, when a fiber optic system is multiplexed, less cable, fewer repeaters, sources, detectors, etc., will be required. This savings is reduced by the increased cost of electronics to perform the multiplexing and, sometimes, by the additional cost necessary to achieve adequate reliability. The FAA generally requires some degree of redundancy in its equipment and a multiplexed system may require a greater percentage of additional equipment to achieve this redundancy.

Multiplexing of the low frequency and control signals is essential because of the large number of optical fibers which would otherwise be required. All of these signals can easily be combined in one video quality channel. This is the recommended approach since it leads to greater commonality of equipment.

The multiplexing of the control signals would be inexpensive, most likely being implemented by a simple microprocessor. The audio and directional signals could be easily modulated on separate carriers to form an FDM system. Because of the high cost of each fiber optic channel, a separate channel for trigger information is unwarranted.

Since the video and trigger do not occur at the same time, it is logical to combine the two for transmission on a single channel. If this is done, care must be taken to insure that the trigger separator does not respond to stray video signals. Two things are necessary if this is to be avoided: (1) the video input to the fiber optic link must be gated off during the radar dead time (time beyond maximum range of the radar but before the next zero time instant), and (2) the trigger separator must be gated on during only this time. The first requirement can be accomplished by simple gating of the video signal with a pulse synchronized to the trigger input. The second requirement can be met by either using the known timing relationships between consecutive triggers or by keying the trigger separator on by supplying a unique gating signal prior to the time that the trigger is expected. The second approach operates on the trigger before it is combined with video and should be more reliable.

SYSTEM TESTING

TEST BED CONFIGURATION.

A block diagram of the recommended test bed is shown in figure 7. It consists of both multiplexed and nonmultiplexed video fiber optic channels. This arrangement was chosen for the following reasons. Two kinds of systems allow comparative testing. Accurate data concerning system performance will allow an intelligent recommendation to be made for field implementation. Along the same lines, the amount of experience gained by the FAA by operating both systems will be almost doubled. Two systems also provide a measure of insurance against unforeseen problems in one system or the other. The additional expense of installing two kinds of systems is small compared to the cost of installing only one because much of the hardware will be common to both systems.

Repeater operation can be implemented by using a jumper at the indicator site to echo signals back to the radar site using the control link. Both regenerative and nonregenerative systems can be implemented in this way.

The fiber optic system including all video multiplexing for both multiplexed and multichannel systems, cable, and installation can be bought off the shelf. The specifications for each of the video channels should be:

0-5 MHz bandwidth,

40 dB dynamic range, and

Probability of false alarm (no signal on channel, threshold 16 dB above noise) $\leq 10^{-6}$.

The low frequency and control/readback multiplexers should be built by the Technical Center. A block diagram of the proposed system is shown in figure 8. Two such systems must be built to accommodate both command and readback function. There are no serious technical problems to overcome in the construction of this device.

SYSTEM TESTS.

Back-to-back testing is accomplished with the hardware transmitter and receiver connected together through an optical attenuator rather than through the actual optical fiber. Back-to-back testing allows measurement of hardware parameters over varying attenuation conditions without the limitations imposed by the cable. Later, when the same tests are performed on the system with the cable in use, the effects of the cable can be isolated. In addition to being a valid set of tests in

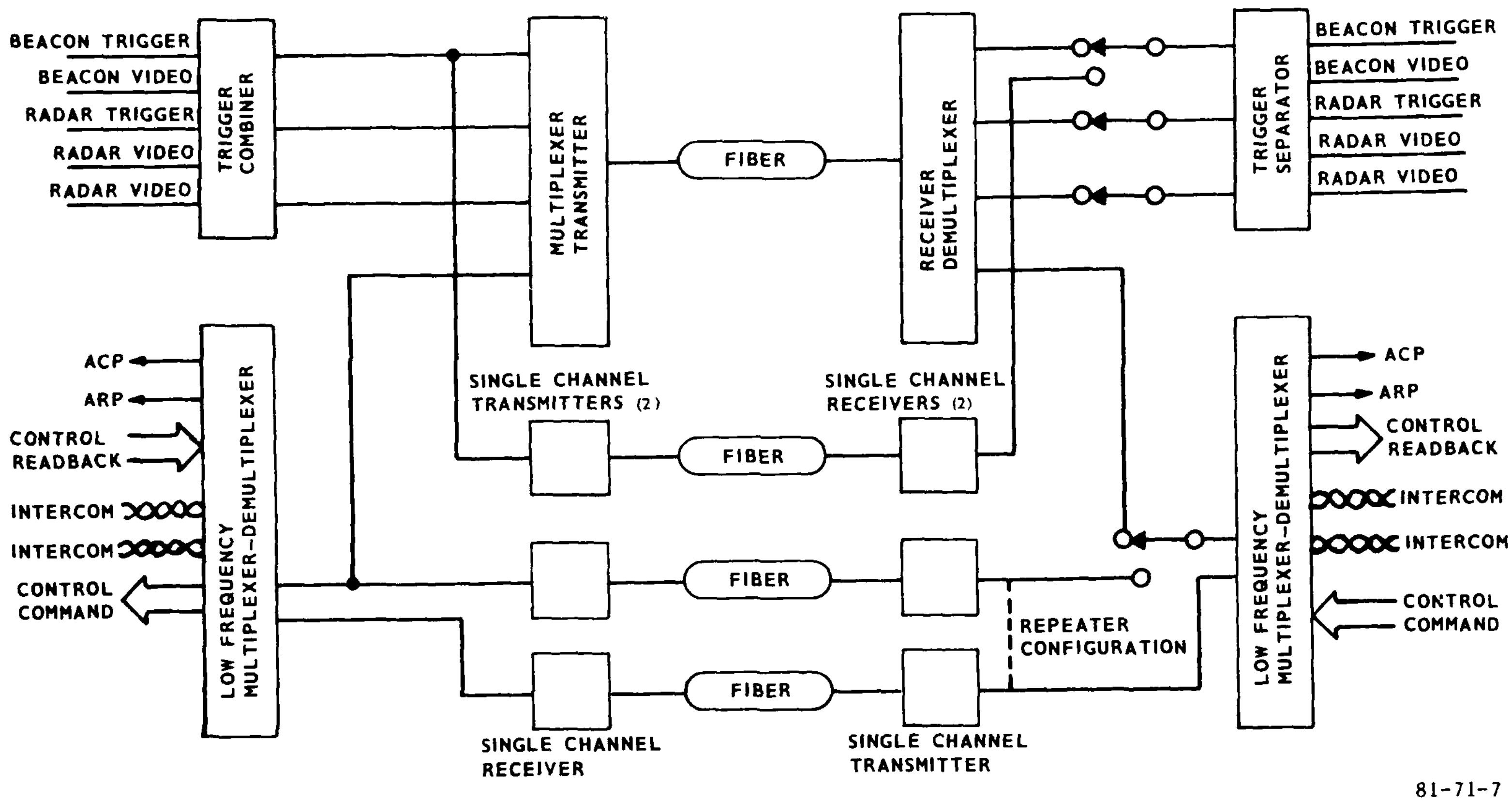

FIGURE 7. BLOCK DIAGRAM OF RECOMMENDED TEST BED

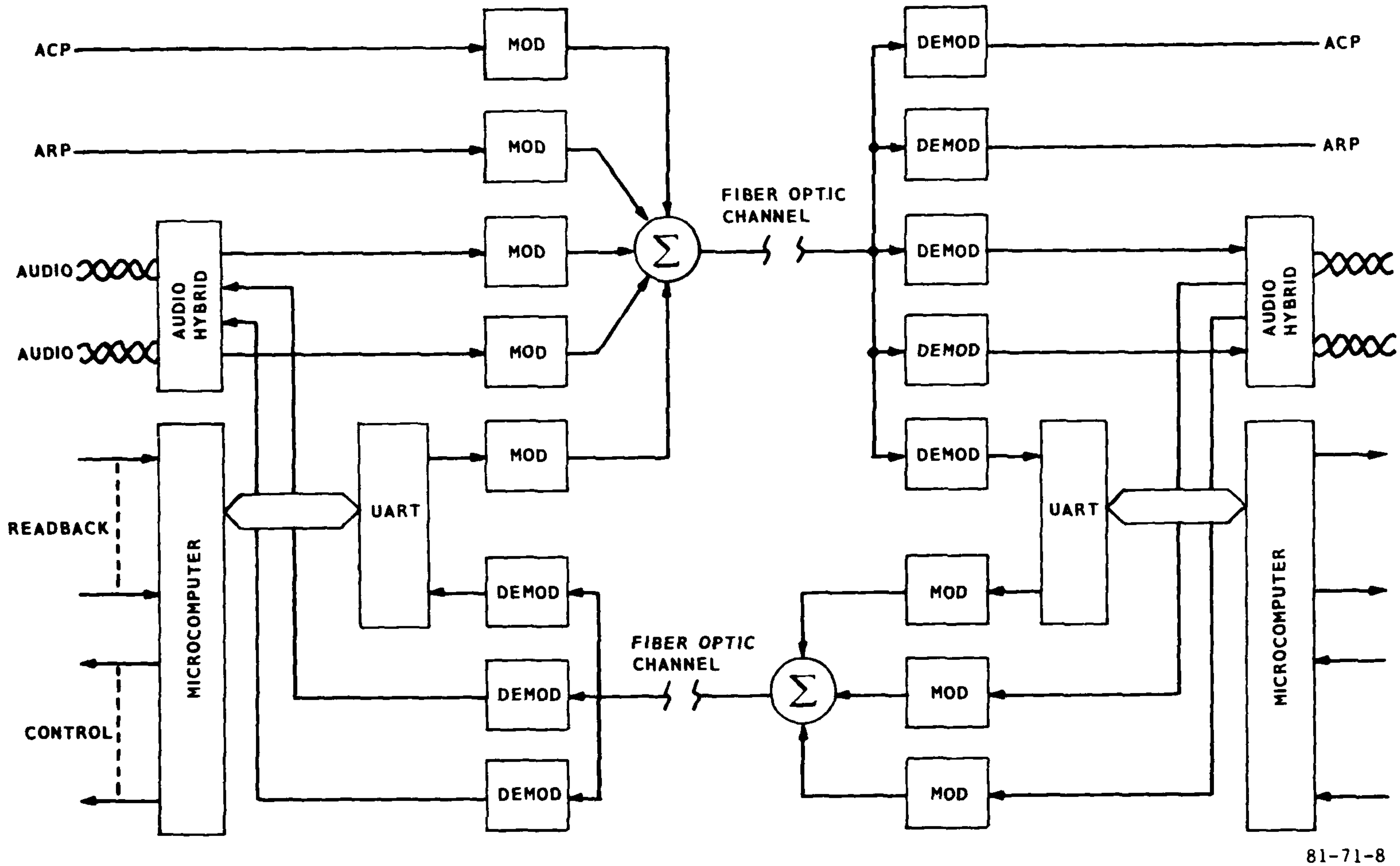

FIGURE 8. BLOCK DIAGRAM OF LOW FREQUENCY MULTIPLEXER DEMULTIPLEXER

their own right, back-to-back tests allow the technicians performing the tests to gain experience in the laboratory before making tests at the site test bed. This is important because field measurements will be made at sites about 4 kilometers distant.

The tests performed in both back-to-back and field tests will measure the following parameters of each channel:

1. Noise Level.

2. Percentage of false alarm versus threshold level to root mean square (rms) noise ratio — this information is used to measure the degradation in detection which will occur as a result of using a given channel. Noise level alone is not a sufficient measurement.

3. Saturation or maximum usable level.

4. System dynamic range — computed by taking the ratio of items 3 and 1.

5. Pulse response — this is a measure of system fidelity. The main concerns are rise time degradation and ringing. Ringing could, if severe, cause false, multiple detections.

6. Frequency response — this is also a measure of system fidelity and important in the low frequency multiplexer operation.

7. Error rate of digital channels.

8. Crosstalk of multiplexed channels — this value is measured with both sinusoidal and pulse signals. Its purpose is to verify that spurious targets will not be detected on adjacent channels (for example, beacon targets on the moving target indicator (MTI) radar channel).

9. Trigger and video stability.

10. Channel-to-channel differential delay — problems in this parameter would cause range errors in the radar detection.

11. Harmonic and intermodulation distortion — these values provide a measure of the interference to be expected in the low frequency multiplexer.

12. Response to simulated failures — evaluates the systems redundancy and error correction detection systems.

These tests will verify the proper operation of the channel. The system will then be configured as it would be in an actual radar site and demonstrated to Airway Facilities and air traffic control personnel. The system will be periodically tested for a period of at least 1 year to insure proper operation and to measure possible aging or degradation of parameters.

HARDWARE SOURCES AND COST.

At the beginning of this study, a letter describing the proposed fiber optic system was sent to 65 manufacturers of fiber optic materials and systems. Thirty-five replys were received. A copy of the letter and a summary of replies is listed in appendix B. Several manufacturers replied indicating that they could supply complete systems, or components which could meet the given requirements. These manufacturers are listed in table 7. A complete list of replies is given in appendix B. Based on this information and estimates from Airways Facilities, Environmental Division, the following cost estimate is proposed.

6-channel fiber optic cable	$24,000
Cable installation 4 km	50,000
Multiplexed link	20,000
Single channel links $5,000 x 5 links	25,000
FAA fabricated hardware	10,000
Test equipment (available)	0
Special tools	1,000
TOTAL	$130,000

SCHEDULE.

	Item	Months
1.	FAA hardware completion	3
2.	Optical link acceptance	start of tests (t)
3.	System test complete	t + 6
4.	System test report	t + 8
5.	Life test complete	t + 14
6.	Life test report (final)	t + 18

SUMMARY

1. A fiber optic remoting system can significantly reduce maintenence costs associated with lightning surges and electromagnetic interference.

2. A channel with a 5 MHz bandwidth and 40 dB dynamic range can adequately transmit both radar and beacon videos.

3. A system meeting the requirements for radar-beacon video transmission can be built with currently available off-the-shelf components.

4. Five 40 dB dynamic range, 5 MHz communications channels are acceptable for radar and beacon remoting. Four of the channels operate from the radar site to the indicator site and may be multiplexed. The remaining channel operates from the indicator site to the radar site.

5. The trigger channel should have a probability of false alarm triggering of less than 10^{-6} and a probability of missed detection of less than 10^{-4}.

TABLE 7. RESULTS OF FIBER OPTICS PRODUCT SEARCH

Manufacturer	Type	Optical Loss Allowed	Bandwidth or Data Rate	Dynamic Range	Remarks
General Optromics Corp.					
Model 60-ANA	Analog Transmitter		20 Hz to 1.256 MHz		1.5 mW output from fiber -40 dB 2nd harmonic distortion -50 dB 3rd harmonic distortion
Model 60-D16	Digital Transmitter		DC-500 Mb/s		3 mW output from fiber 10^{-12} BER from transmitter
Model 60-DIP	Transmitter		1 ns risetime		3 mW output from fiber DIP package
GTE Lenkurt, Inc. Model Fiber Sentry	Analog/Digital	18 dB	CCTV Requirements 3.15 Mb/sec		PIN diode receiver
Model 93321	Digital Tranmitter		44.736 Mb/s		2 mW peak 1 mW average (0 dBm)
Model 93322	Digital Receiver	54 dB			minimum usable input (-54 dBm)
ITT Gilfillan					Fiber optic remoting of SPS-48 radar, TPS-32 radar and phone conversation indicates ASR-8 fiber optic remoting, proposal to Denmark
Lecroy (Radiation Devices) FUS-1	Analog	20 dB	12 Hz to 7 MHz	44 dB	
Meret Model 276TV	Analog	4 km link	10 Hz to 20 MHz	40 dB	Includes transmitter, receiver, cable, test equipment and terminations
Optelcom Model 3100	Analog	15 km link	6 MHz		Indicates 3.5 km, 20 MHz system capabilities
Telemet Model 4210	Analog	10 dB	10 MHz		
Times Fiber Communications, Inc.					Phone conversation indicates requirements can be met
Valtec Model VS-100	Analog	17 dB	18 MHz	54 dB	Also transmits audio and data
ITT Electroptics					Phone conversation indicates requirements can be met

6. A probability of false alarm signals of less than 10^{-4} for the ACP channel and 10^{-8} for the ARP channel is acceptable.

7. Using a laser diode in place of an LED in the optical transmitter results in a signal-to-noise ratio improvement of about 15 dB.

8. Using an avalanche photodetector (APD) in place of a PIN diode in the optical receiver results in a signal-to-noise ratio improvement of about 20 dB.

9. Pulse code modulation and frequency modulation provide significant signal-to-noise ratio improvements over base band and other types of modulation.

10. Digital regenerative repeaters provide performance superior to analog repeaters.

11. Great care must be taken to protect repeaters from electromagnetic interference and lightning induced surges.

12. It is possible to multiplex all required signals on two optical fibers (one fiber used in each direction).

13. It it essential that low frequency and control signals be multiplexed in a fiber optic system.

14. Radar and beacon trigger signals can be multiplexed with the video channels.

CONCLUSIONS

1. Fiber optics technology can be used to remote all airport surveillance radar (ASR) and beacon video, control, azimuth, and audio signals required.

2. The required fiber optic hardware can be obtained off-the-shelf.

3. All control, azimuth, and audio signals can be multiplexed on one video grade channel.

4. Video and trigger signals should be multiplexed onto one video channel.

5. The Federal Aviation Administration (FAA) Technical Center can build all interface and control multiplexing hardware required.

6. The recommended test bed will cost approximately $130,000.00.

7. All of the system tests, including reliability testing, can be completed and a report prepared in 18 months after system acceptance by the Technical Center.

RECOMMENDATIONS

1. Both multiplexed and nonmultiplexed video systems should be installed at the Technical Center so that a comparison of the two systems can be obtained.

2. A repeater should be implemented by echoing signals back to the radar site using the control link hardware.

3. All hardware should be purchased off-the-shelf, preferably from a single manufacturer as a turn key operation, with the exception of the low frequency and control/readback multiplexers which should be built by the Technical Center.

4. The hardware described should be installed at the Technical Center and all system tests described should be performed.

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APPENDIX A

FIBER OPTICS TECHNOLOGY STUDY

APPENDIX A
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APPENDIX A
LIST OF ILLUSTRATIONS

INTRODUCTION

A fiber optic communications link consists of a light source modulated by the message signal, a photo detector to recover the message from the modulated light, and an optical cable to direct the light from source to detector. This paper discusses the function and use of these components in a fiber optic communications system starting with optical fibers and then discussing sources and detectors. The information contained in this appendix is a synopsis of the papers and texts listed in the bibliography.

OPTICAL FIBERS

OPTICAL PROPAGATION AND PULSE DISPERSION.

The step index optical fiber is made by drawing a thin filament consisting of two layers of glass. The outer layer of glass is called the cladding and has a lower index of refraction than the center which is called the core. The operation of this fiber is illustrated in figure A-1. When light in the core is incident on the cladding it will, in general, be refracted according to Snells Law,

$$n_0 \sin\theta_0 = n_1 \sin\theta_1 \qquad \text{(A-1)}$$

n_0 is the core refractive index,
n_1 is the cladding refractive index,
θ_0 is the core angle of incidence, and
θ_1 is the cladding angle of incidence.

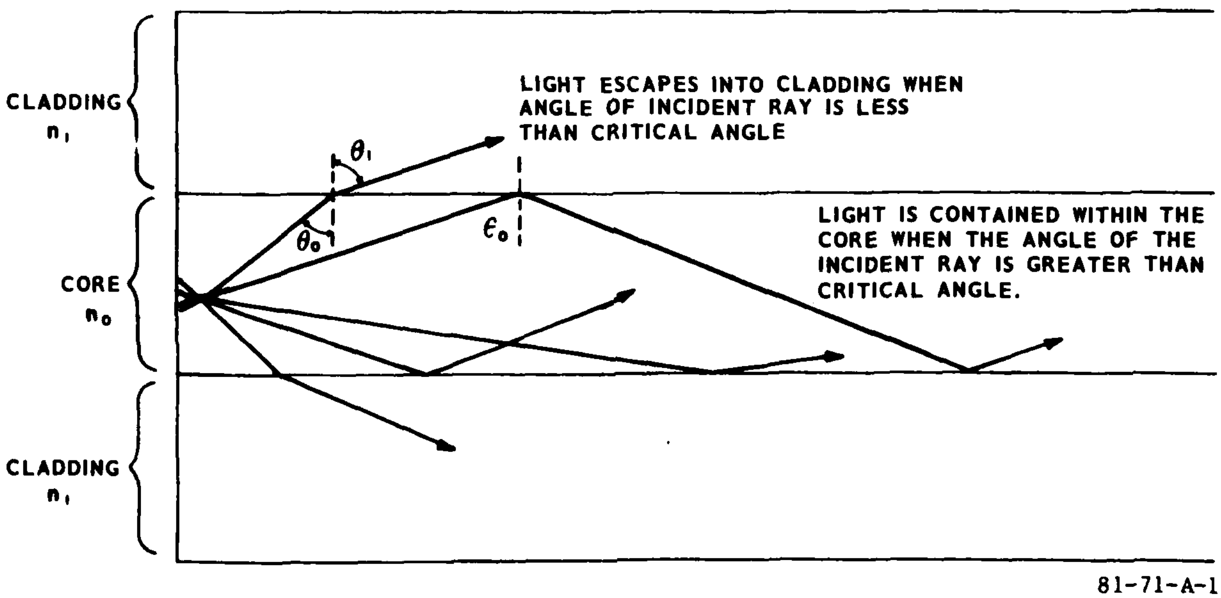

FIGURE A-1. PROPAGATION OF LIGHT IN A STEP INDEX OPTICAL FIBER

For most angles of θ_0, the light will enter the jacket material and be lost. However, for some angles SIN θ_1 is greater than 1 indicating that θ_1 must be a complex number. Physically, this corresponds to the phenonomena of total internal reflection and the light is bound to the core. This condition occurs when SIN $_0$ is greater than the ratio n_1/n_0, the corresponding θ_0 is called the critical angle and is given by

$$\theta_c = \mathrm{SIN}^{-1}\ (n_1/n_0). \qquad \text{(A-2)}$$

Clearly, any ray of light propagating in the fiber at angles less than θ_c will be lost through the cladding. Light propagating in the fiber with angles greater than θ_c will be contained within the core. The velocity of propagation of a light ray in the direction of the fiber axis is of primary concern. A ray with smaller angle of incidence will be reflected a greater number of times and, hence, because the distance propagated is greater, will travel more slowly from one end of the fiber to the other. A pulse of light contains many angles of propagation and, therefore, tends to be spread out in time as it transits the fiber. This effect is called modal dispersion and it limits the available bandwidth of the fiber. Modal dispersion can be reduced by limiting the possible number of angles with which the light can propagate. One way this can be accomplished is to reduce the difference between the core and cladding refractive indices. This will increase the critical angle, θ_c, and, thus, allow a smaller angular semiaperture. The angular semi-aperture is defined as the maximum angular deviation between a bound, propagating ray of light in the core and the axis of the core. The numerical aperture is the sine of the angular semiaperture. High bandwidth fibers have a low numerical aperture, typically 0.2 to 0.3, while lower bandwidth fibers typically have a numerical aperture of about 6.

Until now the light propagation within the fiber has been described by rays of light. This is suitable for reasonably large fibers, but for small fibers the wave nature of light must be considered. When this is done, it is found that only certain angles or modes can exist in the fiber. If the core of the fiber is small enough, with respect to the wavelength of the light, then only one mode, the axial mode, can exist and modal dispersion is eliminated. This kind of fiber is called a single mode fiber. Because of its small size it is more difficult to make and use, hence, it is typically used for only very wide bandwidth applications.

Another way to reduce the modal dispersion is by changing the refractive index profile of the fiber. This leads to the quadratic graded index fiber illustrated in figure A-2. The refractive index of the fiber decreases parabolically from the axis of the fiber. Those modes with greater angles relative to the axis extend further into the lower refractive index region of the cable where the velocity of light is greater. The change in refractive index causes two effects which somewhat offset each other and guide the wave in the fiber. The path of the greater angle modes is larger because it extends further off axis, however, for much of the path length the light is traveling through lower index glass and is, therefore, traveling faster, so the overall delay changes little between modes. Virtually all long distance, high bandwidth cables available today are of this type.

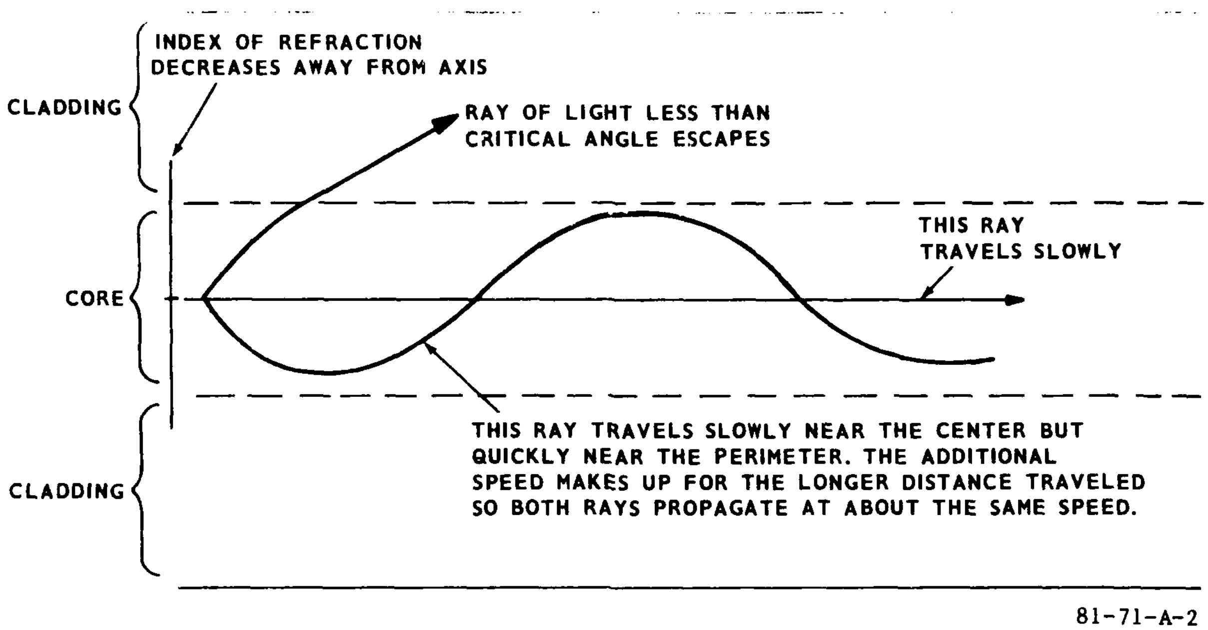

FIGURE A-2. PROPAGATION OF LIGHT IN A GRADED INDEX OPTICAL FIBER

Pulse spreading, sometimes called group velocity dispersion, is also caused by material dispersion. Material dispersion results because the refractive index and, hence, the velocity is a function of frequency. The effect of dispersion is that different frequencies of light propagate at different velocities and, therefore, take different times to transit the length of the cable. The modulation bandwidth of the optical signal will have some effect on the material dispersion, but, except for very stable laser systems, the spectral width of the optical source will predominate. Wide spectral width sources such as light emitting diodes (LED's) will induce greater pulse dispersion than narrow band sources like lasers.

Material dispersion is a linear function of cable length and is also a sensitive function of optical frequency. Thus, specifications for dispersion can only be relied upon for the actually measured optical frequencies. Modal dispersion increases linearly with length up to the equilibrium length, about 1.5 kilometers (km), and increases as the square root of length for lengths greater than the equilibrium length. It is thought that this effect is due to the mixing of modes. That is, a mode of one velocity may, by bending of the cable or other irregularities, induce propagation of another mode of a different velocity, resulting in the average variation of velocity being reduced.

FIBER ATTENUATION.

A second important property of fiber optic cables is the attenuation. Attenuation in a fiber optic cable is due to several factors, the most important of which are: mode coupling, absorption, and Rayleigh scattering.

MODE COUPLING LOSS. Mode coupling loss occurs when the cable is bent, stressed, or deformed in some other way. Low loss modes propagating along the cable may be coupled into modes which are diverted into the cladding and lost. These losses are not constant since they result from mechanical disturbance of the fiber. Expansion and contraction due to temperature changes, vibration, and cable pulling during installation can all result in additional loss. The process of assembling the fiber into a cable can change the cable attenuation by as much as 10 decibels (dB)/km. However, the change is typically on the order of only 1 or 2 dB/km.

ABSORPTION LOSS. Absorption loss is a function of the fiber material. The loss occurs because the molecules of glass or impurities within the glass display an absorption resonance with certain frequencies of light. Because absorption is a resonance effect, it can be highly frequency dependent. The attenuation versus wavelength for several glass fibers is shown in figure A-3.

RAYLEIGH SCATTERING LOSS. Rayleigh scattering also contributes to loss in optical cables. This scattering is due to unavoidable fluctuations of the index of refraction of the material and has a wavelength to the inverse fourth power dependence, hence, it produces less attenuation as the frequency is lowered.

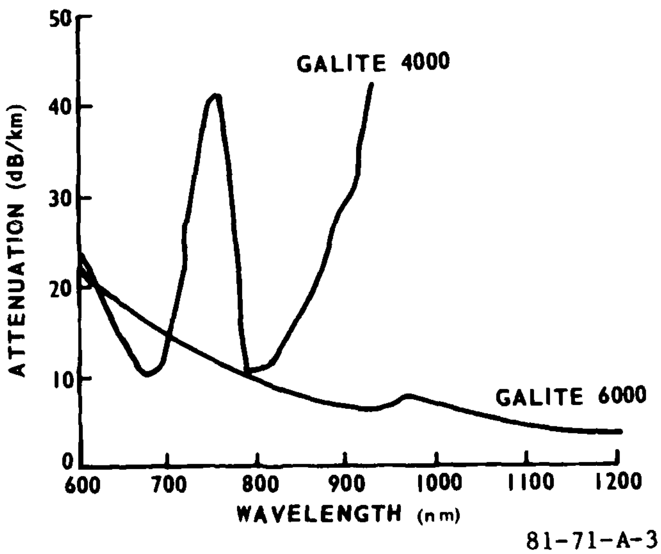

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FIGURE A-3. ATTENUATION VERSUS WAVELENGTH FOR TWO TYPICAL OPTICAL FIBERS

COUPLING LOSS. The attenuation discussed thus far results from properties of the fiber optic cable itself. Additional losses occur when the cable is put into use. Most long fiber optic cable runs require splicing of the fiber optic cable. Loss also occurs when source and detector are interfaced to the fiber. There are three causes of loss at the source to fiber interface: unintercepted illumination loss, reflection loss, and numerical aperture loss.

When the light source is physically larger than the core diameter, some of the light generated will not intercept the core of the fiber. This unintercepted illumination loss can be reduced by making the source smaller than the core and placing the source directly on the end of the fiber core or by focusing the source on the fiber core.

The extent to which focusing can reduce this loss depends on the source radiation pattern. Many LED's have nearly lambertion radiation patterns, meaning that the intensity varies as the cosine of the angle between the axis and the measured direction. In this case, a large source will have the same unintercepted illumination loss when interfaced to a small core whether or not a lens is used for focusing. In the case of a more directive beam, focusing can be used to reduce unintercepted illumination loss.

Reflection loss occurs simply because some of the light incident on the core of the fiber is reflected back away from the fiber. This loss is typically small compared with the other two loss mechanisms discussed.

So called numerical aperture loss results because some of the light that actually enters the fiber core does not develop into a low loss propagating mode bound to the core but, rather, is lost through the cladding.

Light which enters the core will only be bound to the core if it propagates with respect to the fiber axis at an angle that is less than the fiber's angular semiaperture. This is called the acceptance cone. Light which propagates outside of the acceptance cone will be coupled into a high loss mode. When the source is butted directly to the fiber, the numerical aperature loss can be found by considering only the power radiated within the acceptance cone. A lens can be used to improve coupling by directing more of the light produced into the fibers acceptance cone. A lens can improve the coupling by as much as 20 dB, however, an improvement of 13 dB is typical.

Somewhat similar difficulties exist when the detector is coupled to the fiber. Reflections can occur from the end of the fiber causing loss. This is usually negligible. Unintercepted illumination loss can be a problem, however, since the beam is already partially focused, a lens can be used to advantage here if the detector area is smaller than the core diameter. Also, since all of the modes present are already propagating modes, numerical aperature loss is not a problem for the detector.

Splices and connectors present another opportunity for loss. The loss mechanisms for splices and connectors are the same, but the connector losses are usually greater because of the requirement that it be disconnected at times. Splices and connector losses are generated by misalignment, refractive index variations, and core diameter differences. Figure A-4 shows optical fiber splice loss mechanisms.

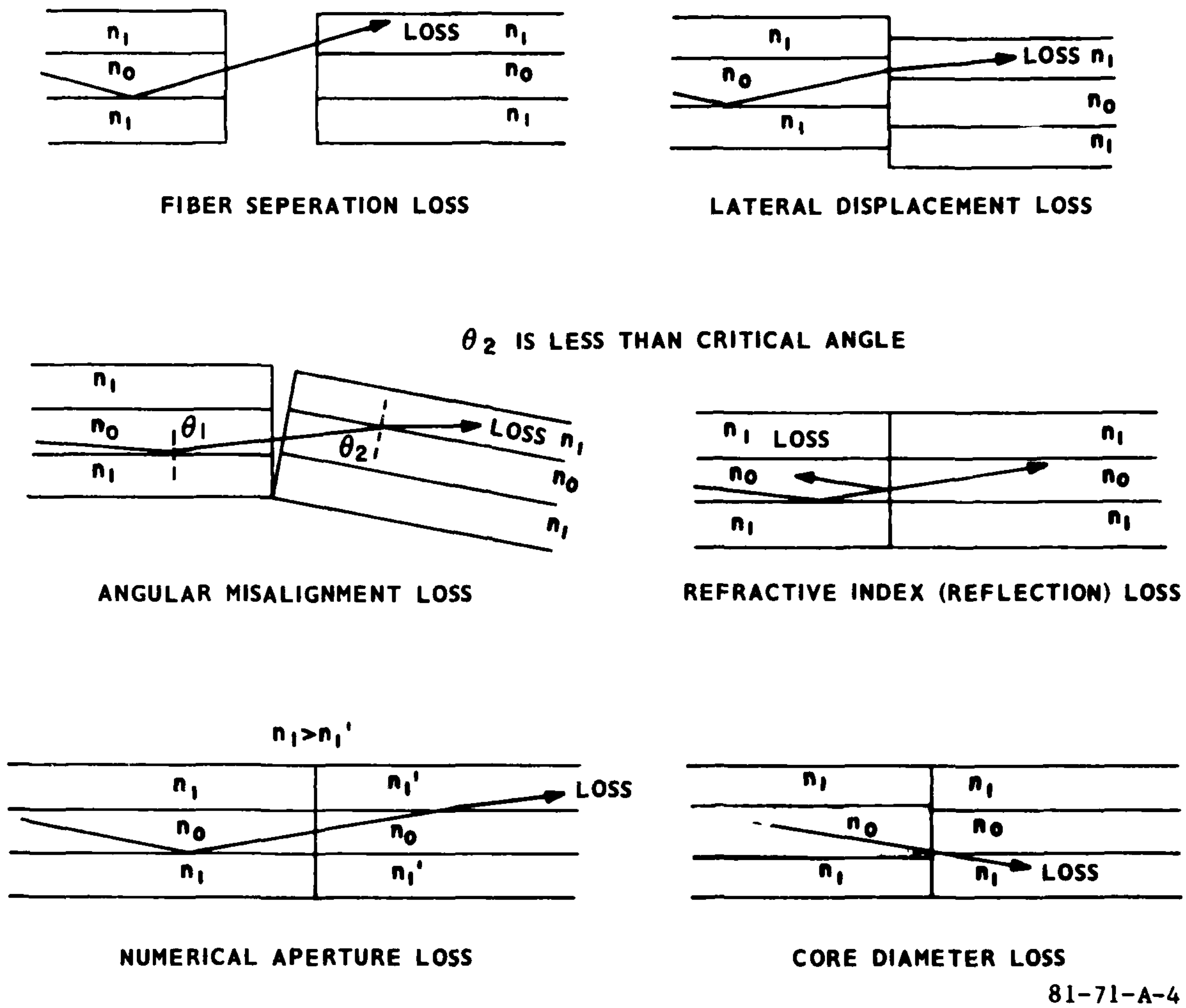


FIGURE A-4. CONNECTOR AND SPLICE LOSS MECHANISMS

Misalignment losses can be controlled by connector design while refractive index loss, core diameter loss, and numerical aperature loss are functions of the fibers to be joined. Losses due to fiber differences can be minimized by restricting connections to fibers of the same type. This is not always possible, particularly when sources and detectors are supplied with integrally connected fiber optic cable pigtails.

Differences in core diameter or numerical aperture both result in converting light from a propagating mode in one fiber to a loss mode in the connected fiber. These losses contribute about 0.15 dB per percent of mismatch, nearly 1 dB for a 6 percent mismatch. Fortunately, if connections of this type are required at all, there should be no more than two, one at the source and one at the detector. Mixing and matching of cable in the middle of a run is definitely not advised.

Refractive index losses occur because of reflection from the boundary at the end of the fiber. Even with fibers of the same type, this is a problem because the ends never mate perfectly. Splices can be assembled either wet or dry. A wet splice has index matching fluid between the ends of the fibers to reduce reflections, a dry splice does not.

Misalignment losses occur because the fibers are not butted together with coincidental axes of propagation. Misalignment occurs with 3° of freedom: axial displacement, lateral displacement, and angular displacement. Axially displaced, the axes remain coincident but the fibers are separated slightly. In the space between the fibers, the guiding property of the fiber is lost and some of the light escapes because the cladding is not present to introduce internal reflection. This loss increases as the numerical aperture increases because the rays of light can then propagate at greater angles from the axis and, thus, are more likely to escape between the fibers. For a fiber of 0.5, numerical aperture, about 1 dB will be lost with a gap spacing of 0.2 times the core diameter.

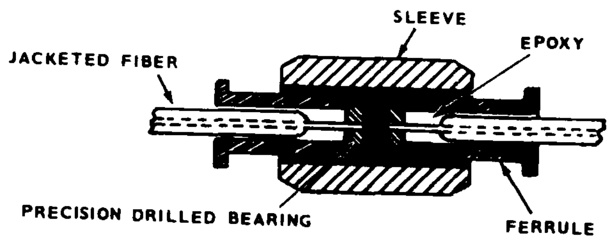
Lateral displacement loss is generated by moving the fibers in a direction perpendicular to the axis but keeping the axes parallel. Some of the core of each fiber will overlap the cladding of the other fiber. Light which propagates in this way is lost. A lateral displacement of 0.2 times the core diameter results in a loss of greater than 1 dB. This requires a movement of only 12 micrometers (μm). Angular displacement loss results when the fiber axes are not parallel. If the fiber ends are considered to be touching (i.e., other losses are neglected), propagating modes will be coupled into nonpropagating modes by the same mechanism discussed in the section on bending loss.

SPLICE AND CONNECTOR TYPES.

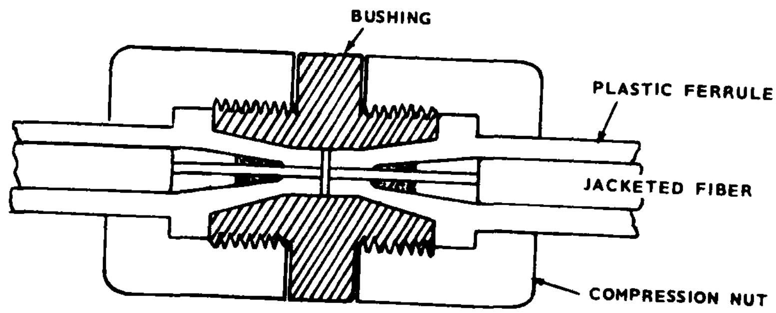
Making consistantly reliable splices of fiber optic cable is more difficult than splicing copper conductors such as coaxial cable. The fibers are small and must be aligned accurately. The ends of the fibers must be flat surfaced and index matched. Fiber splices typically consist of a mechanical fixture to align the fibers, an index matching fluid to mate the fibers, an epoxy or cement to hold the fibers in position, and a protective covering for the splice. The differences between splices are usually in the mechanical fixture used to align the fiber. Several of these are shown in figure A-5.

The first fiber optic connectors were precision machined and patterned after the radiofrequency (RF) connectors already in use, the major difference being that the fiber ends were butted together end-to-end instead of using a conductive sleeve. Precision machined connectors are difficult to manufacture and are susceptible to variations in the fiber diameter. Precision manufacturing makes these connectors rather expensive. Connectors of this type usually have attenuation specifications of below 2 dB. A connector of this type is shown in figure A-5.

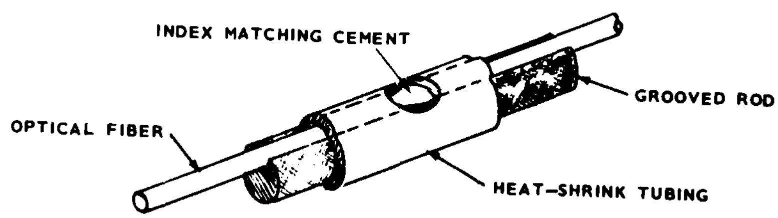
AMP Inc. has marketed a connector (shown in figure A-5) similar to the precision machined type but with an important difference. The ferrule is made of plastic and is held in place by a compression fixture. During manufacture, the ferrule is cast without a hole for the fiber and it is then mounted in a drilling fixture and compressed to its in-service shape. The holes are then drilled and the ferrule removed. When the fiber is inserted and the ferrule is compressed, the fil . lies



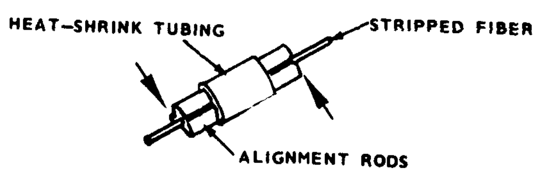
a. PRECISION DRILLED CONNECTOR



b. RESILIENT FERRULE CONNECTOR



c. V-GROOVE SPLICE



d. PARALLEL ROD SPLICE

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FIGURE A-5. CONNECTOR TYPES

in the center of the compression fixture independent of small fiber diameter differences. This connector is easier and less expensive to manufacture than the precision drilled connector.

Another technique, used mostly for splices, is to lay the fibers in a V groove. The parallel edges of the groove act to align the fibers and they are glued together with an index matching epoxy. A similar technique uses parallel rods to surround and align the fibers. These techniques are good only for splices, but they are inexpensive and of good quality. Some have attenuation of about 0.2 dB, and these are to be preferred where cables must be joined only once. These techniques are shown in figure A-5.

Another technique is similar to the V groove but is made as two grooved plastic pieces. These pieces are mounted in connector assemblies and overlap one another when the connectors are joined. The plastic deforms to allow for any variations in the fiber size. Connectors of this type can have attenuation of less than 2 dB.

Most all types of splices and connectors have been adapted to multifiber use. To insure good fiber-to-fiber interfaces the ends of the fibers must be specially prepared. This is accomplished by either cleaving or polishing.

A fiber is cleaved by bending the fiber and applying tension along the fiber. The edge of the fiber toward the outside of the bend is scored causing a crack to propagate across the fiber, leaving a flat end surface perpendicular to the fiber's axis. Two fibers can be butted against one another with good accuracy, but an index matching fluid will improve the loss characteristics.

A fiber is polished by breaking it and then inserting the broken end in a special fixture and grinding it flat using progressively finer abrasives. This technique is generally thought to produce a slightly better result than cleaving, but it may not be justified because of the extra work required to achieve this result. Connector and splice manufacturers usually specify the end of the cable. When a fiber is to be interfaced to a source or detector, a lens is sometimes formed by melting the end of the fiber to form a small bubble of glass. This is done by holding the fiber in a fixture and observing the end with a microscope while heating the end of the fiber with a small flame from an oxy-acetylene torch. When the end of the fiber melts, the surface tension of the glass forms the lens. Care must, of course, be taken and the technique requires some practice. It is not supposed to be difficult to learn.

After end preparation, the fibers can be aligned with one of the connectors or splices, discussed above, and either be fixed in place mechanically with clamps or epoxied into place. Epoxy is preferable since it will not come loose and is usually recommended by manufacturers. Fibers are also sometimes melted together but this technique is better suited for laboratory applications.

OPTICAL CABLE.

Optical fibers must be cabled before they can be used. Cabling protects the fiber from the stress of installation, especially from pulling and bending. It also protects the fiber from its surroundings, preventing things like contamination and rodent damage. The cable prevents excessive bending, which could cause added loss or even breakage. Cabling also contributes to ease of handling and allows convenient multifiber arrangements.

Each fiber of a cable is surrounded by a buffer material. The purpose of the buffer is to isolate the fiber from external stress on the cable. It is generally made of a soft, flexible material. If the fiber is in complete contact with the buffer, the fiber is said to be tightly buffered. If it is contained in a space within the buffer material, it is said to be loosly buffered. Of the two techniques, the loose buffer may be slightly more resistent to axially applied stress. Not much difference seems to exist in practice between the two methods. The buffer is covered with a more rigid layer of plastic and the entire cable is often armored with steel tape. The cable also contains a strength member, usually either steel or kevlar depending on the application. Copper conductors are sometimes included to power repeaters or carry control signals. Cables are made for nearly any kind of installation including duct, aerial, and direct burial.

LIGHT SOURCES

Commercial fiberoptic communications systems use either laser diodes (LD) or LED's for light sources. Large continuous wave lasers have been proposed for long distance systems, but are too expensive and bulky for most systems. Continuous sources also require electro-optic modulators, further increasing both size and expense. Diode lasers and LED's can be self-modulated and provide acceptably bright light for the great majority of applications.

LED OPERATION.

As the name implies, LED's are diodes. A diode is a junction of two different semiconductor types, called N or P. Current does not readily flow through pure semiconductor material because the electrons, which could normally be expected to move (i.e., the four valance electrons), are held tightly in place by the crystal structure. A material of this type is called an intrinsic semiconductor. Impurities, called dopants, are deliberately added to intrinsic semiconductors to form N- or P-type semiconductors. N-type impurities have one more electron in the valance band. Only four of these impurity electrons are bound to the crystal; the extra electron is free to move. This allows current flow to take place. P-type impurities have one less electron in the valance band than the semiconductor, and here a gap or hole is formed. Neighboring electrons bound to the crystal can easily move into this hole. When this happens, a new hole forms at the place where the electron came from. Effectively, the hole has moved; semiconductor physicists call this method of current flow, hole conduction.

Holes are positively charged and electrons are negatively charged. When N-type material comes into contact with P-type material, some of the electrons combine with the holes creating a region on both sides of the junction called the depletion region. This is the place where the holes and electrons interact most readily. When an electric potential is applied across the junction so the N-type material is more negative than the P-type material, the junction is said to be forward biased. Forward biasing a diode causes current to flow. Electrons flow from the N-type material into the junction; holes flow from the P-type material into the junction. In the depletion region, the electrons and holes combine, lowering the total energy. This excess energy can be given up in two forms: light (photons) and heat (i.e., molecular vibration). Electrons and holes need not have the same momentum in the crystal. If they do not, the excess momentum from the hole-electron collision is transferred to the crystal, thus generating heat. This is called *indirect recombination*. Direct recombination occurs when both electron and hole have exactly opposite momentums and no excess momentum exists upon recombination. Direct recombination results in only light output. Materials chosen for LED's allow mostly direct recombination, but certain places in the crystal, particularly near flaws or impurities, allow indirect recombination. These sites are called *nonradiative centers* and result in a lowered efficiency for the LED.

The generation of light by this combination of electrons and holes is called spontaneous emissions. Electrons can also be removed from the valance band by reacting with a photon of light. The photon is absorbed by the crystal and an electron hole pair is formed. This effect is put to good use in photo detector diodes and transistors. In LED's, it causes attenuation of the light as it passes through the crystal.

LASER DIODE OPERATION.

If a photon interacts with an electron which has not yet combined with a hole, an interesting effect occurs — the electron is stimulated to combine with a hole and the resulting photon is emitted in the same direction and with the same phase as the initial photon. This is called stimulated emission. If few electrons are excited, stimulated emissions will be of little consequence since the probability of a photon interacting with an excited electron will be small, and light traveling through the crystal will be attenuated. However, if the number of excited electrons in the crystal is large, then stimulated emission will occur frequently and the light wave may be amplified. The condition that exists when enough electrons are excited to allow this amplification to occur is called a population inversion and it is caused by supplying sufficient current density to the junction of the diode. The minimum current necessary to cause amplification in a laser diode is called the threshold current (I_t). A laser is more than an amplifier though, it is an oscillator. To create an oscillator from an amplifier, feedback must be introduced. This is accomplished by cleaving the ends of the crystal perpendicular to the junction so light can be reflected back and forth through the amplifying region. The population inversion necessary for amplification must be maintained or the laser operation will cease. The population inversion can be reduced by two methods: spontaneous emission and stimulated emission. In other words, the very act of generating or amplifying light reduces the lasers ability to oscillate. At values of current near threshold, the laser oscillation may stop until the population inversion is again achieved. This leads to relaxation oscillations.

SYSTEM DEPENDENCE ON SOURCE PARAMETERS.

The selection of a source is critical to the operation of a system. It is the device that allows conversion of electrical signals to optical signals. It critically effects the bandwidth, signal-to-noise ratio, and cost of the system. The parameters of both lasers and LED's will be discussed to provide a basis for system decisions. Each of the important source parameters will be discussed.

EMISSION FREQUENCY. The emission frequency of both lasers and LED's is determined by the energy band structure within the junction. This band structure is shown in figure A-6. The difference in energy between the noncombined and combined state of the electron determines the frequency of emission. The band structure, in turn,

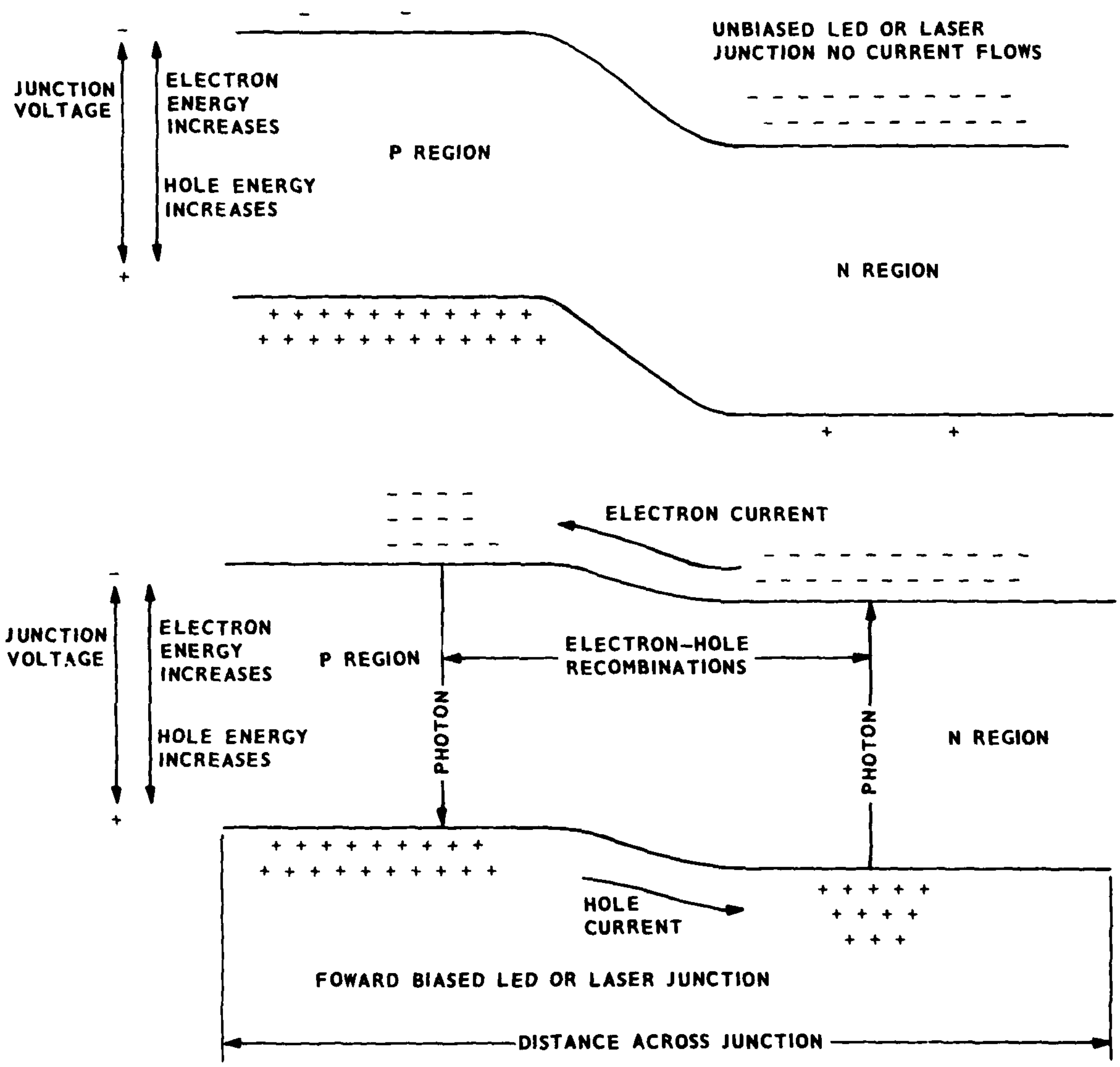

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FIGURE A-6. LED OR LASER DIODE JUNCTION ENERGY DIAGRAM is determined by the semiconductor material and the kind and amount of doping impurities. Most systems in operation commercially use emission wavelengths of between 0.800 and 0.900 μm. Other systems operate near 1.1 and 1.3 μm. This is a result of current optical fibers being most transparent in these ranges and not because of an inability to produce devices of other frequencies. It is important to use an LED or laser that operates in the low loss region of the fibers attenuation characteristic. Not all fibers are the same, and small differences in emission wavelength can cause significant attenuation in some fibers.

One of the limitations on system bandwidth is the material dispersion of the fiber caused by the spectral width of the source. The width of the emission frequency of LED's is determined by the width of the energy bands in the diode junction. The individual atoms of any material have very sharp (narrow bandwidth) spectral characteristics. However, when a material exists as a crystal, the adjacent atoms interfere with each other to effectively widen the energy bands. Electrons can now have a wider range of acceptable energies and will, thus, emit different frequencies upon recombination. The LED has spectral width of about 0.05 μm.

Laser amplification can occur roughly over these same frequencies. However, the amplifying material exists between two reflecting surfaces which form a highly frequency selective resonant cavity. It is this cavity that is responsible for the narrow spectrum of the laser emissions. The semiconductor laser has a spectral width of about 0.004 μm. The laser is much less limited by material dispersion than the LED.

LINEARITY. A device is said to be linear if increasing the input by some margin causes the output to increase by the same margin. LED and lasers are not strictly linear because attempting to operate the device with a negative current input (reversed biased) results in no output at all. A device can be said to be locally linear (of operating in a linear region) if, at some operating point, small changes in the input cause linear changes in the output. When an LED is forward biased, the light output is directly proportional to the current input and so the LED is linear over this region. The laser exhibits a current threshold before it turns on; additional current above threshold causes the light output to increase rapidly. This characteristic is shown in figure A-7. The laser can be made to operate more linearly if a constant current slightly greater than threshold is added to the input current.

It is impossible to completely characterize linearily by examining graphs such as figure A-7. One reason for this is that the degree of linearity is difficult to measure. Another reason is that small nonlinearities can have a great effect on some systems. Any system nonlinearities will cause mixing of different signal frequencies and, therefore, produce intermodulation distortion. This problem is particularly troublesome when two or more different signals are frequency multiplexed on the same fiber optic channel. The laser, even when biased above threshold, is usually less linear than a comparable LED. As a result, the LED may be preferred for multiplex systems.

POWER OUTPUT. The source power output is important because it affects the signal-to-noise ratio and maximum link length attainable. Laser diodes are capable of outputting about 10 times the power of LED's. Since the laser beam is much more directive than the LED beam, more of the light produced by the laser will be within the fiber's acceptance core.

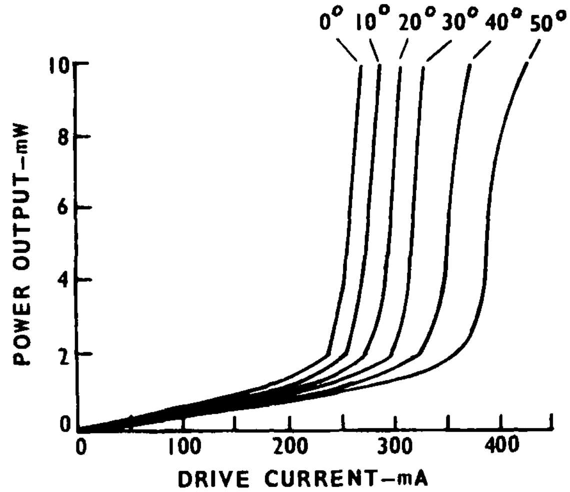

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FIGURE A-7. TYPICAL LASER DIODE POWER OUTPUT VERSUS DIRECT CURRENT FORWARD BIAS

<u>MODULATION CAPABILITY</u>. A carrier (i.e., a hole or an electron) that is injected <u>into the junction of</u> an LED or laser diode will recombine with another carrier of opposite polarity. This does not occur immediately. The average time before recombination occurs is called the carrier life time and is symbolized by (τ). When the light output of the diode is modulated by varying the injection current, the carrier lifetime determines the frequency response. Consider the case of injecting a very narrow current pulse. Some of the carriers will recombine quickly while others take much longer; therefore, light from this pulse is spread out in time, reducing the frequency response. This effect is expressed quantitively as:

$$\frac{P(w)}{P(0)} = \frac{1}{(1 + (w\tau)^2)^{1/2}} \qquad \text{(A-3)}$$

where: w is the radian frequency in sec^{-1},

τ is the carrier lifetime in seconds,

P(w) is the power output in watts when the diode is modulated at frequency, and

P(0) is the power output, in watts, for d.c. modulation.

Because of stimulated emission, the lifetime of carriers in laser diodes is small, hence, lasers have a greater modulation capability. LED's can be typically modulated at frequencies on the order of tens of megahertz, while lasers can be modulated on the order of hundreds of megahertz. Lasers, however, suffer from problems that LED's do not. Figure A-8 shows a laser being turned on from a completely off state. When the laser starts to work as the current increases above threshold, the carriers are quickly depleted. The laser may even turn off for a short time. This process, called relaxation, can occur several times before steady state is reached. An output like that shown in figure A-8 will result. Since relaxation occurs only near the threshold, lasers are usually biased slightly above threshold to eliminate the relaxation problem as shown in figure A-8. As previously mentioned, this increases linearity as well.

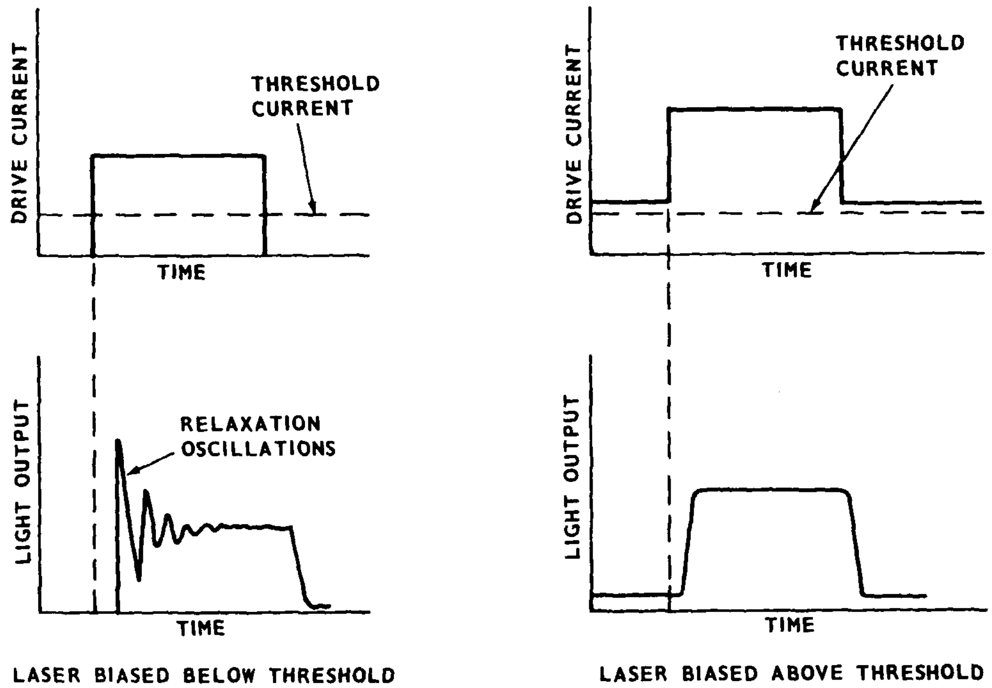

FIGURE A-8. LASER PULSE RESPONSES

TEMPERATURE DEPENDENCE. All semiconductor diodes are temperature dependent; the LED and laser diode are not exceptions. This temperature dependence is manifested by a decrease in light output as the temperature increases. For the LED, simple compensation is used to increase the applied current when the temperature increases, correcting the dependence. This technique does not work well for the laser diode because the threshold varies with temperature. The slope of the transfer function above the threshold varies with temperature as well. This is illustrated in figure 5. For higher temperatures the curve also becomes less linear.

Two approaches to the temperature dependence problem are used: feedback compenstion and brute-force temperature control. The brute-force method attempts to control the diode's temperature by using large heat sinks and thermoelectric cooling. In addition to maintaining more consistent diode parameters, the reduced temperature variation improves reliability by reducing the thermal shock. One problem with the brute-force technique is the time lag introduced by the thermal resistance of the semiconductor between the junction and the heat sink. This problem is overcome by using feedback compensation. The output of the laser diode is monitored by a photodetector and the current injected is controlled to provide a desired light output. Variations in temperature are adaptively compensated for by this technique, but the temperature itself can change. The best solution is to use both methods simultaneously if the increased reliability and performance is worth the additional expense.

RELIABILITY. Any device generating light for fiber optic communications over medium or long distances must, of necessity, generate a large amount of optical power over a very small area. This power density and the current density necessary to produce it are responsible for the most common failure mechanisms of LED's and lasers. Current densities for LED's are about 1,000 amperes per square centimeter, while current densities of between 5,000 and 15,000 amperes per square centimeter are not uncommon for lasers. This difference coupled with the smaller emitting surface of lasers causes catastrophic failures to occur in laser diodes more often than in LED's (10^5 hour or less meantime between failure (MTBF) compared to about 10^6 hour MTBF. The tremendous field strength of these devices causes disturbances of the crystal near the cleaned edge of the laser diode. This is called facet damage. Facet damage can be reduced in two ways: by applying an anti-reflective coating to the crystal face or by reducing the power output of the laser. Facet damage occurs most frequently near flaws in the crystal where the bands between atoms are typically weaker than normal.

Another kind of damage is gradual degradation. Gradual degradation increases the laser threshold and reduces the efficiency of both LED's and laser diodes. This degradation is usually of greater concern for LED's because their longer life is limited by this factor. Gradual degradation is thought to occur because the current flow through the diode causes migration of impurities and the formation and enlargement of nonradiative recombination centers. Some work indicates that this effect may be reduced somewhat by reverse biasing the junction periodically while the diode is in use. This, of course, will turn off the device.

The third type of failure is caused by temperature cycling. This causes fractures in the crystal itself, and in the crystal-to-fiber epoxy bond. Temperature control, as discussed in the preceding section, will help prevent this problem.

PHOTODETECTORS

The purpose of a photodetector is to convert light into electrical current. For fiber optics applications the detector used must be sensitive and wide band. It must be reasonably insensitive to temperature, low in cost, and have a long lifetime. It should respond linearly to changes in incident light intensity.

Several photodetector types are used in fiber optic communication. Photomultipliers are used for measurements of light intensity in the lab, but are not used as receivers in practical systems because of their large size and high cost. They are, however, efficient, sensitive, and have relatively low noise. Photodiodes are used extensively as receivers in fiber optic systems since they meet nearly all of the requirements for a good detector. Photodiodes can loosely be thought of as inverse LED's. Rather than generating light by combining electrons and holes, the photodiode allows a current to flow by separating electrons and holes when light is absorbed in the diode junction. Phototransistors are similar to photodiodes in operation, but differ in that pair production (electron hole) occurs in the base of a transistor, thus, stimulating a larger current flow between the collector and the emitter. Phototransistors are typically slow, exhibit some nonlinearity, and are generally not used. Henceforth, in this discussion, detector will be used to mean a photodiode.

OPERATION OF PHOTODIODES.

A common photodiode is a PN junction built so light can enter and be absorbed in the junction's depletion region. Light striking the atoms of the semiconductor material excite electrons from the valance band of the atom into the conduction band. This leaves a hole. The hole and electron are commonly called a pair. If the diode is reverse biased, current will not normally flow through the junction region; however, any pairs which are formed will contribute to a current flow. The depletion region usually contains no carriers and, therefore, exhibits a high resistance. By comparison, the N and P material to either side of the junction are fairly good conductors. Most of the voltage drop occurs across the junction causing pairs generated within the depletion region to quickly separate and leave the junction. This movement is called drift and it is responsible for most of the light induced current flow. If a photon excites an atom in the P or N region rather than the depletion region, the electric field is weak and, unless the hole or electron quickly diffuses into the junction region where the strong field exists, it will recombine and not contribute to current flow.

It is clearly advantageous to have all (or at least most) of the photons interact in the depletion region. As was the case for sources, photons can interact either directly or indirectly. An indirect interaction means that a phonon (crystal vibration quantum) is required in addition to a photon to generate a pair. There is still a one photon to one electron-hole pair relationship, but the probability of interaction is greatly reduced.

Germanium is typically used as a direct interaction detector. Nearly all of the incident light is absorbed within 1 micrometer. Silicon, on the other hand, exhibits indirect interaction and requires 50 micrometers for the incident light to be absorbed. A silicon diode must have a junction at least 50 micrometers deep to achieve optimum efficiency. The PN photodetector is shown in figure A-9.

PIN DIODE OPERATION.

One of the limitations of the PN diode photodetector is the small depletion region. The thickness of the depletion region is inversely proportional to the dopant concentration. If the concentration in the material near the junction is reduced, the depletion region will extend farther to that side. This is the principle of the PIN diode. The construction of the PIN diode is shown in figure A-9. The region labeled I is nearly intrinsic but lightly doped as N material. The strongly doped N region supplies good electrical contact between the I region and the metalization used for the connection lead. Because of the lightly doped I region, the depletion region is greatly extended. PIN diode quantum efficiencies are typically 0.8, meaning that 80 percent of all photons entering the diode are converted into conduction pairs.

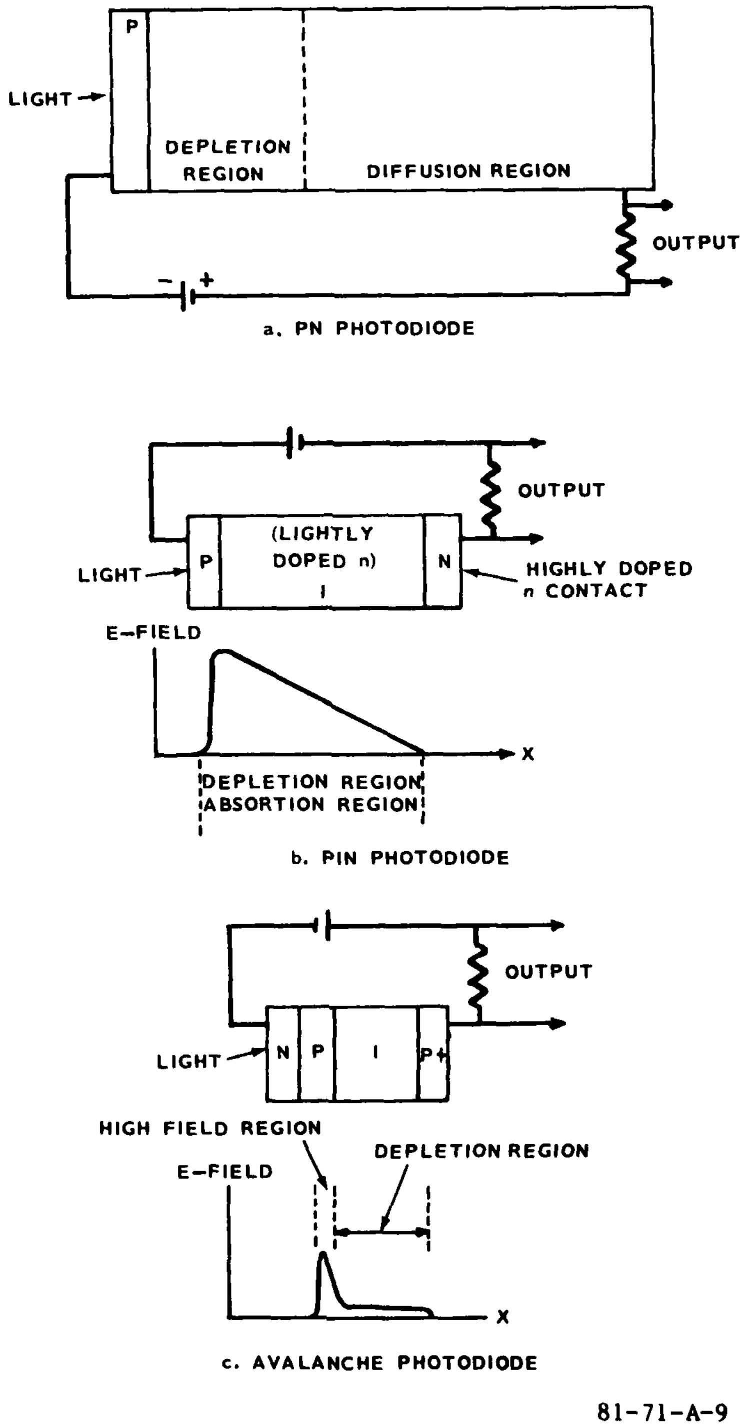

FIGURE A-9. PHOTO DIODE CONSTRUCTION

AVALANCHE PHOTODIODE OPERATION.

The avalanche photodiode (APD) is operated at a high reverse bias voltage. Electrons and holes formed in the intrinsic region are quickly accelerated to a velocity where an impact with an atom will excite the creation of another electron-hole pair. This process, called impact ionization, continues resulting in a large number of electrons and holes being generated for only one photon impact. The avalanche photodiode, therefore, has a gain. Gains of about 100 are typical. The holes and electrons tend to zig-zag back and forth through the junction region. It is never certain exactly how many pairs will be created by a single photon. This uncertainty is manifested as an additional noise which will be seen to limit the maximum performance of the avalanche photodetector. An improved structure for the APD is shown in figure A-9. The avalanche region is separated from the light sensitive I region. This configuration produces better noise characteristics because the gain of the avalanche stage no longer depends on the place in the junction where the pair generation takes place.

SYSTEM DEPENDENCE ON DETECTOR PARAMETERS.

The first choice to be made in selecting a detector is the selection of either a PIN photodiode or an avalanche photodiode. Simple PN photodiodes do not have the quantum efficiency or speed to be useful for fiberoptic communication applications. As was done for sources, each of the significant parameters will be discussed and related to the operation of APD's and PIN photodiodes. The most important considerations for device selection are frequency response and noise, as is the case with most receivers.

DETECTION RESPONSE. Unlike LED's and lasers, photodiodes have relatively broad spectral responses. The incident photon must have an energy greater than the energy of the band gap between the valance and conduction band. This establishes the lower cutoff frequency. As this frequency (and, thus, the energy) increases, the probability of interaction also increases and, for a while, the response also increases. If the frequency is increased beyond a certain value, the probability of pair production increases so much that large numbers of photons are being absorbed before the I region can be reached. This results in the weaker diffusion current and, thus, the response decreases. Because of the wide spectral response of the photodiode, it is only necessary to choose a detector which is responsive in the proper band of frequencies. For operation at 0.8 micrometers, silicon detectors are commonly used.

DETECTOR EFFICIENCY. The current produced for a given light power incident on a detector is dependent on four factors: detector gain, reflections from the detector surface, the internal quantum efficiency, and the frequency of the incident radiation. The frequency of the incident radiation affects the detector efficiency in two ways: (1) the frequency response of the detector changes as discussed in the preceding paragraph, and (2) the energy per photon increases with increasing frequency. Since more photons are required for a given energy, this second effect tends to favor a lower frequency for fiber optic transmission. If the quantum efficiency remains reasonably constant, a shift to lower frequency photo detectors will allow greater distances between repeaters. This trend can be noticed in the increased number of long wavelength systems being tested recently.

Quantum efficiency is the ratio of generated conduction pairs to incident photons and is typically 0.8. It is a function of the detector material.

To eliminate reflection from the front surface of the crystal, a quarter wavelength coating is sometimes applied to the crystal surface. Because a quarter wavelength is necessary, the frequency response of the detector can be narrowed. If anti-reflective coating is used, the source and detector must be carefully matched. The gain of the avalanche photodetector has a direct and obvious relationship to the detector efficiency. The current generated in the intrinsic region is simply multiplied by the avalanche gain. It is important to remember that detector efficiency is not sensitivity. Sensitivity must account for the noise in the measurement while the detector efficiency does not.

MODULATION FREQUENCY RESPONSE. The modulation frequency response of photodiodes is determined by three factors: the finite diffusion time of carriers created outside of the depletion region, the transit time through the depletion region, and the junction capacitance of the diode. The diffusion time limitation is small in practical diodes because of the large intrinsic region. Ideally, very few photons are generated outside of the depletion region. Transit time affects the frequency response because of the delay introduced by the finite drift time. Carriers generated near the edge of the depletion region quickly contribute to the detector current, while carriers away from the edge must travel farther and introduce delay. This effect is exaggerated in avalanche photodiodes because of the time necessary for the generation of a hundred or so additional carriers. In most practical diodes, this effect is small compared to the junction capitance effect. The primary modulation frequency limiting effect is junction capacitance. This capacitance is effectively in parallel with the amplifier input impedence and forms a low pass circuit with a cutoff of about 1/RC (R is the input indepence, C is the junction capacitance). The cutoff frequency can be extended in two ways: (1) the junction can be made smaller, thus, reducing the capacitance C or, (2) the amplifier input inpedence R can be made small. Reducing the resistance has serious consequences when noise is considered, as will be explained in the next section.

SENSITIVITY. Sensitivity is a measure of the smallest signal that can be detected by the diode. If it were not for noise, any signal, even a single photon could be detected. Noise introduces error and a good measure of performance is signal-to-noise ratio (SNR). The minimum detectable signal is defined, somewhat arbitrarily, as the signal level necessary to make the SNR unity. The greatest sensitivity is achieved by maximizing the SNR. In the following, several important detector noise mechanisms will be discussed before the total SNR is computed. Finally, the effect of avalanche gain will be discussed.

Thermal Noise. Thermal noise is generated by the random motion of charge carriers within a material. It is called thermal because the random motion within the material is measured by the materials temperature. Noise power available from a resistor of resistance R is proportional to the temperature and the bandwidth of interest. The proportionality constant is Boltzman's constant K. The power that such a noise source will supply to an external matched load is:

$$P_t = KTB \tag{A-4}$$

where:

P_t is the thermal noise power in watts,

K is Boltzmann's constant,

T is the temperature, in degrees Kelvin, and

B is the bandwidth in hertz (Hz) over which the power is measured.

Maximum power transfer occurs when the source resistance and load resistance are equal. If the source resistor is modeled as a noise current source in parallel with a noiseless conductance, G = 1/R, then the mean square thermal noise current of this current source is:

$$I_T^2 = \frac{4KTB}{R.} \tag{A-5}$$

Shot Noise. Shot noise is generated by the discrete nature of electrical current. Shot noise in photodiodes is generated by four mechanisms: spontaneous carrier generation responsible for diode leakage, current generation by the signal, current amplification by avalanche effects, and current generation by background light. Background light does not exist in a fiber optic system, so the mean square shot noise due to electric current flow is given by

$$I_{sn}^2 = 2\ e\bar{I}B \tag{A-6}$$

where:

I_{sn}^2 is the mean square shot noise current in amperes squared,

e is the electron charge in coulombs,

$\bar{I}$ is the average current in amperes, and

B is the bandwidth of the measurement in Hz.

I_{sn} is proportional to the average current and the bandwidth over which the noise is measured.

Shot noise generated by the dark current (leakage) is given by

$$I_{dn} = 2e\bar{I}_dB \tag{A-7}$$

where:

$\bar{I}_d$ is the diode leakage current.

The current generated by light incident upon the diode is found by taking the product of the number of photons incident on the detector, the electron charge, e, and the quantum efficiency, η. The quantum efficiency is the ratio of electron hole pairs generated to the number of incident photons. The number of incident photons per unit time is found by dividing the power incident on the detector by the energy per photon, given by $h\nu$, where h is Planck's constant and ν is frequency. This current is found to be

$$I = \frac{PMe}{h\nu} \tag{A-8}$$

where:

I is the light induced current in amperes,
P is the optical power in watts,
h is Plancks constant,
ν is the optical frequency in Hz,
η is the quantum efficiency,
e is the electron charge in coulombs, and
M is the avalanche gain.

Inserting this value into equation A-6 results in

$$I_{in}^2 = 2(P/h\nu)\eta e^2 B \tag{A-9}$$

where:

I_{in} is the mean square shot noise current resulting from the incident light.

However, because of effects due to the modulation of the light signal have not been considered in this simplified analysis, a better estimate, given by Yariv (reference 1) is

$$I_{in}^2 = 3(p/h\nu)\eta e^2 B \tag{A-10}$$

The effect of avalanche gain is to multiply both the signal induced and dark current induced shot noise currents. If the photon induced current is multiplied by a value M, then the mean square current is multiplied by M^2. It has been shown by McIntyre (reference 2) that if only electrons or only holes are responsible for avalanche gain, the shot noise follows this same relationship. However, if both electrons and holes contribute, a somewhat higher multiplication factor, as much as M^3, may be required. It has been experimentally determined that $M^{2.1}$ is reasonable in most cases.

Signal-to-Noise Ratio. Since the signal power and noise power are acting on the same impedance, the SNR can be expressed as a ratio of current squared rather than power. The current produced by a signal or power P in a diode with an avalanche gain of M is M times the previously determined light induced current

$$I_a = (P\eta/h\nu)eM \tag{A-11}$$

where:

I_a is the avalanche diodes light induced current.

So the mean squared light induced current for an avalanche diode is

$$I_a^2 = 2[(P\eta/h\nu)eM]^2 \tag{A-12}$$

Again, the factor of two results because of modulation. Dividing this value by the sum of the previously derived noise mean squared currents yields

$$SNR = \frac{2[(P\eta/h\nu)eM]^2}{\left(\frac{3P\eta}{h\nu} e^2 M^2 B + 2eI_d BM + \frac{4KTB}{R}\right)} \tag{A-13}$$

The noise bandwidth for a simple RC circuit is given by 1/RC. Because R must be small to allow sufficient bandwidth for most systems, the thermal noise term

$$\frac{4KTB}{R}$$

will dominate for small values of M. For PIN diodes, M = 1 and the shot noise can be neglected resulting in a signal to noise ratio of:

$$SNR_{(PIN)} = \frac{1}{2}\,\frac{(P\eta e/h\nu)^2}{KTB/R} \tag{A-14}$$

The SNR can be increased by increasing the power (P), quantum efficiency (η), or amplifier input resistance (R); or by decreasing the temperature (T), bandwidth (B), or the frequency of the light (ν). For small values of M, the SNR will increase as M as long as the thermal noise term dominates. However, as M increases, the shot noise term in the denominator begins to dominate and, at this point, since the denominator grows a little faster than the numerator, the SNR will decrease again. The optimum value of M is different for different diodes, but usually lies in the range of 30 to 100. A detector operating in this range is said to be quantum limited and the SNR neglecting the leakage current,

$$SNR_{(APD)} = \frac{2P\eta/h\nu}{3BM^{0.1}} \cong \frac{0.42}{h\nu}\,\frac{P\eta}{B}\ . \tag{A-15}$$

The S/N ratio can now be increased by increasing power (P) or efficiency (η), or by decreasing signal bandwidth (B).

TEMPERATURE DEPENDENCE. As in the case of LED's and laser diodes, both PIN and avalanche photodiodes are temperature sensitive. The band gap change has little effect on these diodes since they are operational at frequencies well above cutoff. However, in the case of the avalanche diode, the multiplication factor is highly temperature dependent. Either the temperature must be controlled or the current must be changed as the temperature varies. The second approach is most often taken. Again, feedback techniques are used. One approach monitors a second APD thermally coupled to the detector APD. The gain of the reference APD is measured and kept constant by varying the bias voltage. The same bias voltage is used for both APD's, so the gains of both devices should be nearly equal. Another technique uses the detector current to change the bias volgage. This is not as accurate because of the uncertainty of the input, but is suitable for many applications.

RELIABILITY. There is no serious reliability problem with photodiodes, however, the selection of a detector can affect system reliability indirectly. The more sensitive APD may be chosen over a PIN diode to allow the use of the more reliable, but lower power, LED rather than the laser diode in some applications.

SUMMARY

1. The two kinds of optical fiber available are step index and graded index fibers.

2. Pulse dispersion is significantly greater in step index fibers than in graded index fibers.

3. Fiber optic cables have high transparency (low attenuation) only at certain frequencies.

4. Attenuation is increased by stressing the fiber beyond specified limits.

5. Splice losses are on the order of 0.2 dB.

6. Connecter losses are on the order of 2 dB or less.

7. Optical fiber cable is available for duct, aerial, and direct burial use.

8. LED's and laser diodes are used exclusively for fiber optic communication sources.

9. LED's have a wider spectrum and, therefore, cause greater material pulse dispersion than lasers.

10. LED's are inherently more linear than lasers.

11. Lasers can couple about 10 times more power into an optical fiber than LED's.

12. The modulation bandwidth of laser diodes is inherently greater than LED's.

13. LED's are less sensitive to temperature than laser diodes.

14. LED's have a greater lifetime than lasers.

15. PIN photodiodes and avalanche photodiodes are used exclusively for fiber optic communications detectors.

16. Photodiodes have a broad spectral response.

17. Photodiode quantum efficiency is on the order of 0.5 to 0.8.

18. Modulation frequency response is primarily limited by the diode junction capacitance.

19. PIN diodes are thermal noise limited.

20. APD's can be quantum (shot noise) limited.

21. PIN diodes are much less temperature sensitive than APD's.

22. APD's and PIN diodes have no serious reliability problems.

23. Electrical signal power is proportional to optical signal power squared.

REFERENCES

1. Yariv, Amnon, Introduction to Optical Electronics, Holt, Rinehart, and Winston, 1976.

2. McIntyre, R., Multiplication Noise in Uniform Avalanche Diodes, IEEE Transactions on Electronic Devices, Vol. ED-13, 1966, p. 164.

APPENDIX B

RESULTS OF MANUFACTURERS STUDY

A survey of fiber optics manufacturers was conducted by sending a letter to each of the companies listed in table B-1. The companies were selected from advertisements and fiber optics articles listed in trade magazines and from a directory of electronics manufacturers. No attempt was made to censor names from the list. A summary of replies is listed in table B-2.

TABLE B-1. MANUFACTURERS CONTACTED

A. C. Interface Inc.
2925 College Avenue
Costa Mesa, California 92626

American Optical Corp.
Sci. Instr. Div.
Eggert and Sugar Roads
Buffalo, New York 14215

AMP Special Industries
Valley Forge, Pennsylvania 19482

Amphenol North America Div.
Bunker Ramo Corp.
900 Commerce Drive
Oak Brook, Illinois 60521

Augat Interconnection Products Div.
Dept. E
33 Perry Ave., Box 779
Attleboro, Massachusetts 02703

Automatic Connector Inc.
400 Moreland Road
Commack, New York 11725

Belden Corp.
2000 S. Batavia Avenue
Geneva, Illinois 60134

Bell & Howell
Control Products Div.
706 Bostwick Ave.
Bridgeport, Connecticut 06605

Breeze-Illinois, Inc.
Main & Agard Sts.
Wyoming, Illinois 61491

Burr-Brown
P.O. Box 11400
Tucson, Arizona 85734

Cannon U.S.A., Inc.
10 Nevada Dr.
Lake Success, New York 11040

GTE Sylvania, Inc.
Electronic Systems Group
1800 N. Kent St.
Washington, D.C. 22209

Canoga Data Systems
6470 Eton Avenue
Canoga Park, California 91303

Corning Glass Works
Telecomm Products
Corning, New York 14830

Dolan-Jenner Industries, Inc.
Box 1029
Woburn, Massachusetts 01801

DuPont Co.
Plastic Products and Resins Dept.
Wilmington, Delaware 19898

E. G. & G.
Electro Optics Div.
35 Congress St.
Salem, Massachusetts 01970

FG Engineering Co.
Box 39
Mayer, Arizona 86333

Fiberoptic Cable Corp.
Box 1492
Framingham, Massachusetts 01701

Fiber Optic Cable and Components
Amp Inc., Box 3608
Harrisburg, Pennsylvania 17105

Galileo Electro-Optics Corp.
Galileo Park
Sturbridge, Massachusetts 01518

General Cable
Communications Products Operation
1 Woodbridge Center
P.O. Box 700
Woodbridge, New Jersey 07095

General Optronics
3005 Hadley Road
Plainfield, New Jersey 07080

Motorola Semiconductor Products
M370
Box 20912
Phoenix, Arizona 85036

TABLE B-1. MANUFACTURERS CONTACTED (CONTINUED)

Harris Corp.
Electronic Systems Div.
Box 37
Melbourne, Florida 32901

Hewlett-Packard Co.
1501 Page Mill Rd.
Palo Alto, California 94304

Hughes Aircraft Co.
Aerospace Groups
Centnela Ave. & Teale St.
Culver City, California 90230

IPC Centronic
1101 Bristol Rd.
Mountain Side, New Jersey 07902

ITT Cannon Electric
666 E. Dyer Rd.
Santa Anna, California 92702

ITT Electro Optical Products Div.
7635 Plantation Rd.
Roanoke, Virginia 24019

Jan Hardware Mfg. Co.
427 36th St.
Long Island City, New York 11101

Laser Diode Laboratories Inc.
205 Forrest St.
Metuchen, New Jersey 08840

Math Associated, Inc.
376 Great Neck Road
Great Neck, New York 11021

Maxlite Optical Wareguides
Box 11288
Phoenix, Arizona 85061

Meret Inc.
1815 24th St.
Santa Monica, California 90404

Radiation Devices Co., Inc.
Box 8450
Baltimore, Maryland 21234

NEC America
2990 Telstar Court
Suite 212
Falls Church, Virginia 22042

Olektron Corp.
6 Chase Ave.
Dudley, Massachusetts 01570

Optelcom Inc.
15940 Shady Grove Rd.
Gaithersburg, Maryland 20760

Opcoa Div. of IDS, Inc.
330 Talmadge Rd.
Edison, New Jersey 08817

Opcon Inc.
720 80th St. SW
Everett, Washington 98203

Photodyne Inc.
5356 Sterling Center Dr.
Westlake Village, California 91361

Poly-Optical Products
1815 E. Carnegie Ave.
Santa Anna, California 92705

Power Technology, Inc.
Box 4403
7925 Mablewave Cutoff
Little Rock, Arkansas

Pulsar Assocs.
11491 Sorrento Valley Rd.
San Diego, California 92121

Quartz Products Corp.
688 Somerset St.
Plainfield, New Jersey 07061

Thermal American Fused Quartz
Change Bridge Road
Montville, New Jersey 07045

Thomas and Betts
T&B Opto-Electronics Tech. Group
Raritan, New Jersey 08869

TABLE B-1. MANUFACTURERS CONTACTED (CONTINUED)

RCA
Electro-Optics and Devices
New Holland Ave.
Lancaster, Pennsylvania 17604

Schott Optical Glass Inc.
York Avenue
Duryea, Pennsylvania 18642

Siecor Optical Cable, Inc.
631 Miracle Mile
Horseheads, New York 14845

Skan-A-Matic Corp.
Box S
Elbridge, New York 13060

Spectronics Inc.
830 E. Arapho Rd.
Richardson, Texas 75080

3M Company
Electronic Products Div.
3M Center
St. Paul, Minnesota 55101

T & B Ansley Corp.
3208 Humbelt St.
Los Angeles, California 90031

TC Centronic
Kings Henry's Dr.
Addington, Croydon CR9 OBG
Great Britain

Telemat Co.
185 Dixon Ave.
Amityville, New York 11701

Texas Instruments, Inc.
Box 225012-MS-84
Dallas, Texas 75265

Times Fiber Communications Inc.
358 Hall Ave.
Wallingford, Connecticut 06492

Trompeter Electronics, Inc.
8936 Comanche
Chatsworth, California 91311

TRW Cinch Connectors
1501 Morse Ave.
Elk Grove Village, Illinois 60007

United Detector Technology
2644 30th St.
Santa Monica, California 90405

Valtec Corp.
Electro Fiberoptics Div.
West Boylstown, Massachusetts 01583

Varian Associates
611 Hansen Way
Palo Alto, California 94303

Welch Allyn, Inc.
Indl. Products Div.
Skaneateles Falls, New York 13153

TABLE B-2. LIST OF RESPONDING MANUFACTURERS AND THEIR FIBER OPTICS RELATED SPECIALTY

Manufacturer	Specialty
ITT Electro Optical Products Division	Medium and long haul single channel and multiplexed video systems
AMP Inc.	Connectors
Augat Interconnection Products Division	Connectors, short haul digital links
Burr Brown, Dept. EM	Short haul links and cable
Hewlet-Packard Co.	Short haul links
3M Company	Short haul links
Photodyne Inc., Dept. EM	Test Equipment
Power Technology, Inc.	Lab Equipment and splicers
Pulsar Associates, Dept. EM	Short haul analog link
American Optical Corp.	Not applicable
Corning Glass Works	Optical fiber
Gallelo Electro-Optics Corp.	Optical cable
Meret Inc.	MDL276TB medium haul video link
Motorola Servicander for Products	Components
Radiation Devices Co. (LECROY Fiber Optic Systems)	Medium haul video link
Siecor Optical Cable, Inc.	Optical cable
Skam-A-matic Corp.	Not applicable
Telemet Co.	10 dB Optical loss, analog video system
Trompeter Electronics, Inc.	Connectors and cable
Welch Allyn Inc.	Not applicable
DuPont	Plastic cable (high loss)
Quartz products Inc.	Optical cable
Times Fiber Communications Inc.	Multiplexed video system

TABLE B-2. LIST OF RESPONDING MANUFACTURERS AND THEIR FIBER OPTICS RELATED SPECIALTY (CONTINUED)

Manufacturer	Specialty
Valtec	Medium and long haul video links
E. G. & G	Not Applicable
RCA	Components
Spectranics Inc.	Components
LASER Diode Laboratories Inc.	Laser Sources
Maxlite Optical Wave Guide	Optical Cable
OPTELCOM, Inc.	Optical Transmitters
TRW Cinch Connecters	Connecters
General Optronics	Laser Transmitters
Texas Instruments	Not Applicable
Varian	LED Sources
GTE Lenkurt, Inc.	18 dB Optical Loss, Analog Video System

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